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HARVARD & SMITHSONIAN

Non-Gamma-ray Applications of TeV Telescopes

Michael Daniel

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36th ICRC 25th July, 2019

Outline

- How is a TeV telescope useful for non-TeV science?

- Eclipses/Occultations/Transits

- Intensity Interferometry
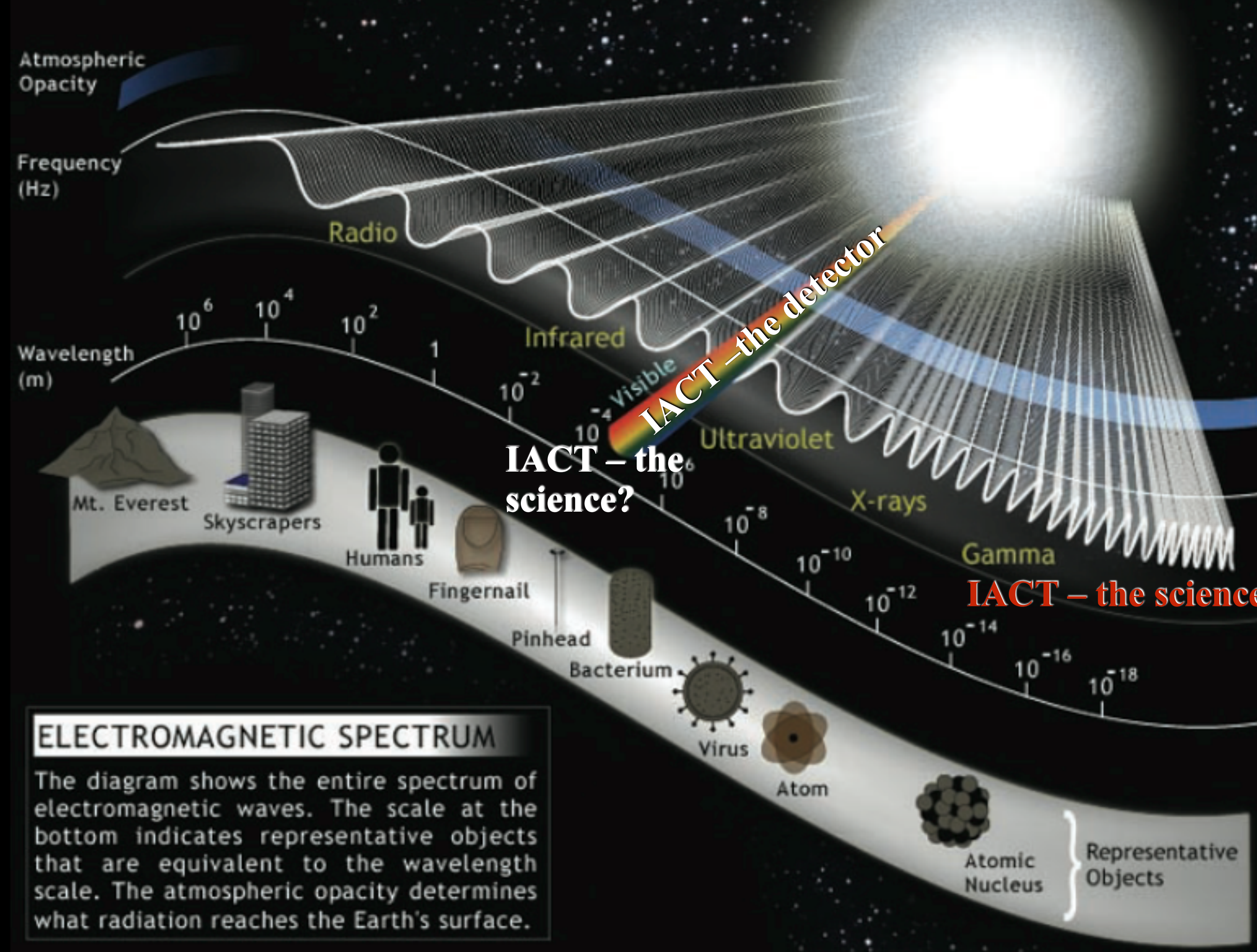
- Optical Communications

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- eclipses (binaries)
- occultations (asteroids/KBOs/
- transits (exoplanets)
- intensity interferometry
- OSETI
- FRB counterparts
- …

IACT – the detector

IACT – the science?

ELECTROMAGNETIC SPECTRUM

The diagram shows the entire spectrum of electromagnetic waves. The scale at the bottom indicates representative objects that are equivalent to the wavelength scale. The atmospheric opacity determines what radiation reaches the Earth's surface.

IACT – the science

- SNR
- Pulsars/PWN
- Binaries
- AGN
- DM/LIV
- …

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Noise sources in optical astronomy

$$\sigma^2 \simeq \sigma^2_{\text{flicker}} + \sigma^2_{\text{scintillation}} + \sigma^2_{shot}$$

Source   Atmosphere   Detector

Flicker

Scintillation

Shot

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Noise sources in optical astronomy

$$\sigma^2 \simeq \sigma^2_{\text{flicker}} + \sigma^2_{\text{scintillation}} + \sigma^2_{shot}$$

Source   Atmosphere   Detector

But we can do something about this with the detector

8m class

Scintillation noise

Shot noise

Osborn et al MNRAS 452, 1707 (2006)

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Temporal Power Spectrum of Scintillation

i) $\sigma_{I,se}^2 = 17.34 D^{-7/3}(\cos\gamma)^{-3} \int_0^{\inf} h^2 C_n^2(h)\mathrm{d}h$

ii)

iii) $\sigma_{I,le}^2 = 10.66 D^{-4/3} t^{-1}(\cos\gamma)^{-\alpha} \int_0^{\inf} \frac{h^2 C_n^2(h)}{v_\perp(h)} \mathrm{d}h$

D=1m

bigger = better

Dravins (1998) - 2m extrapolation
Young (1969) - 4" extrapolation

Osborn (2006) - 8m class

D=12m

caveats depends on
wind speed
wind direction
altitude
airmass
central obscurations …
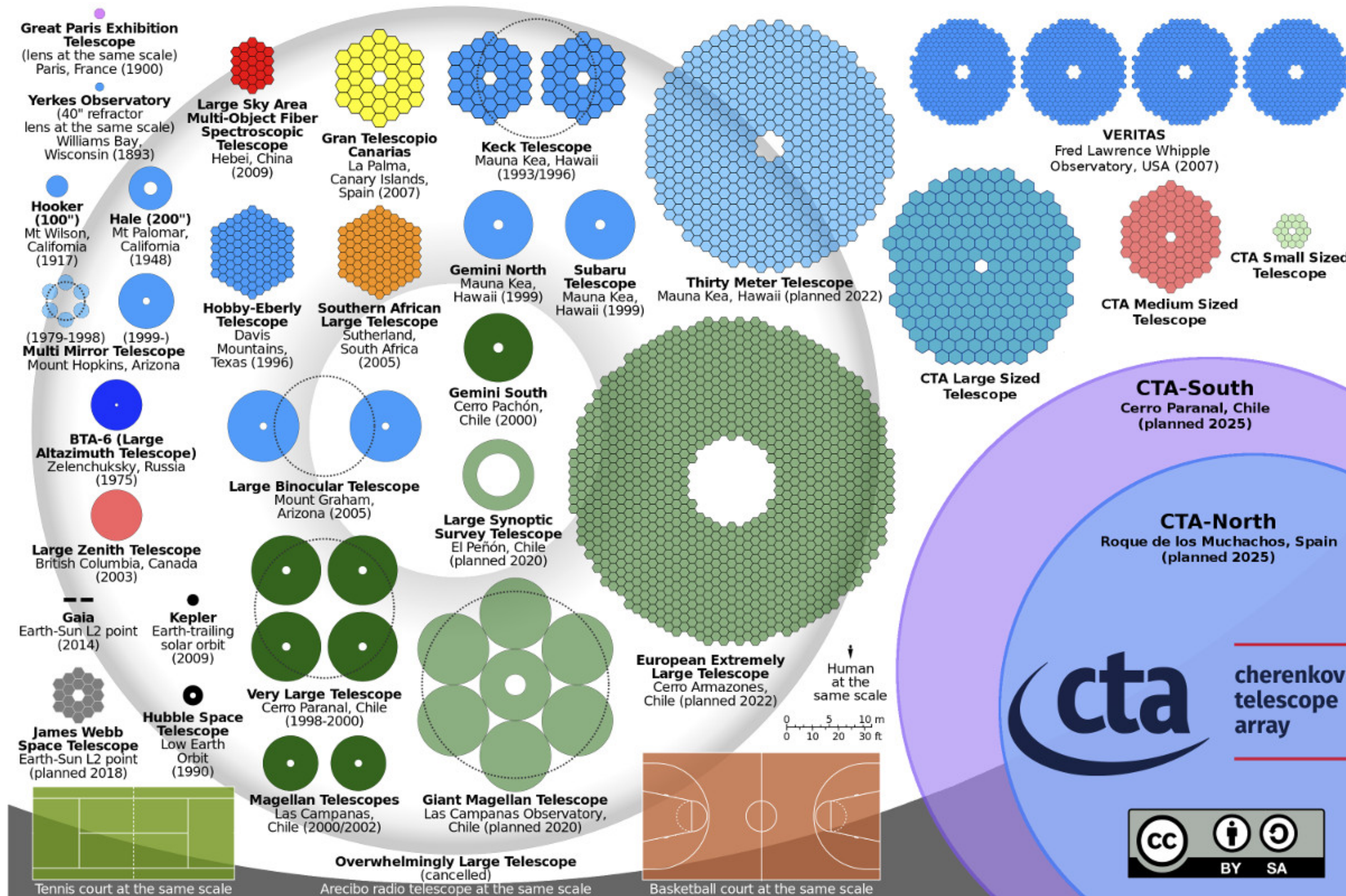
Median Scintillation Noise [arb.]

Exposure [s]

Scintillation is complex process

i) short exposure regime
  • speckles appear frozen
  • no temporal averaging
ii) ~size of speckles
  • significant wavelength dependence
iii) long exposure regime
  • speckles traverse pupil
  • noise reduced by temporal averaging

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Temporal Power Spectrum of Scintillation

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If bigger = better

CMG Lee / T. Hassan

Then Cherenkov telescopes should rank among the best (in terms photometric capability)

So what sort of optical things have been done with IACTs?

36th ICRC - Madison 2019

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Whipple 10m first to measure meteors down to 12th magnitude
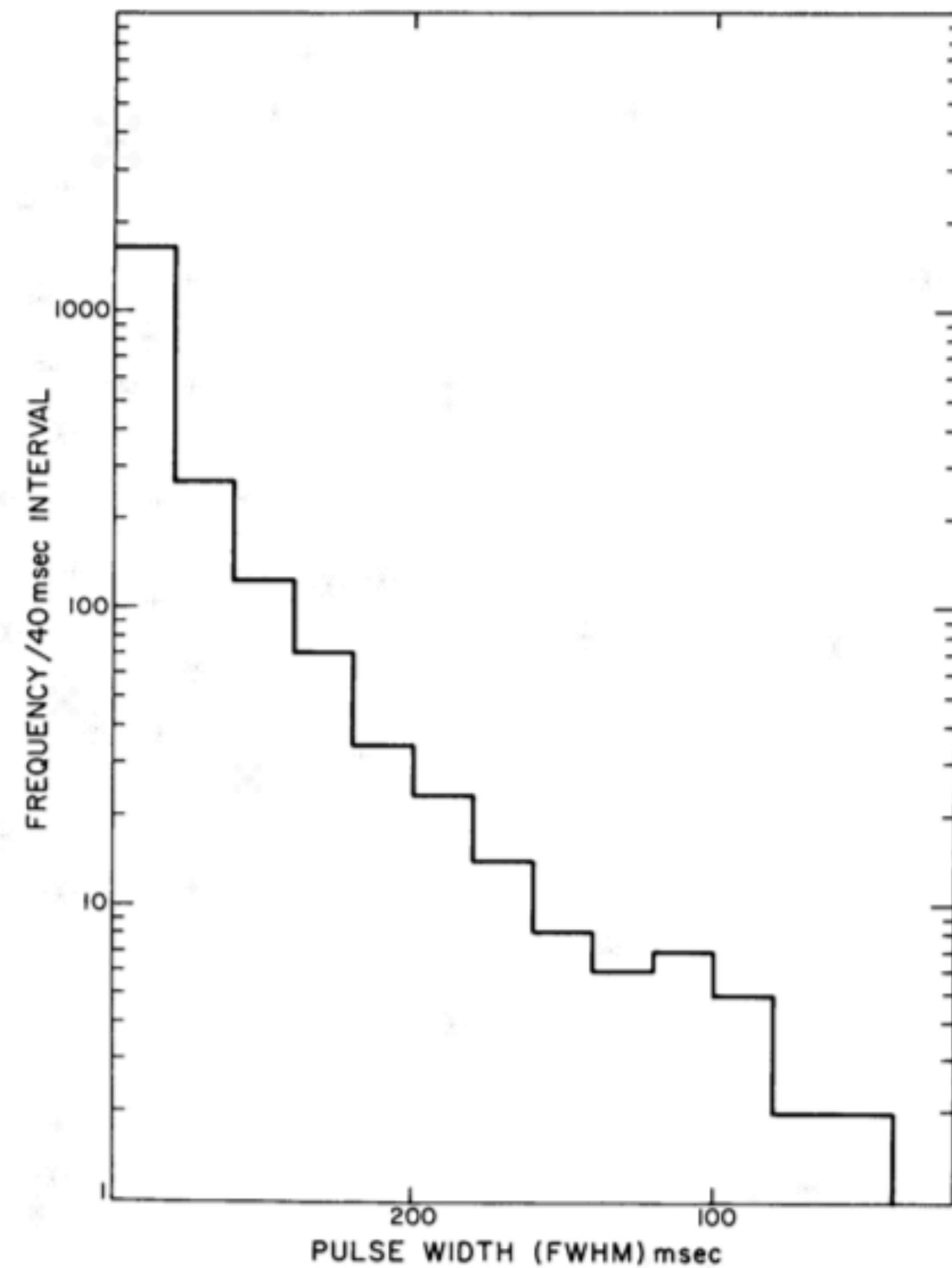
Figure 4. The distribution of pulse widths with time (FWHM).
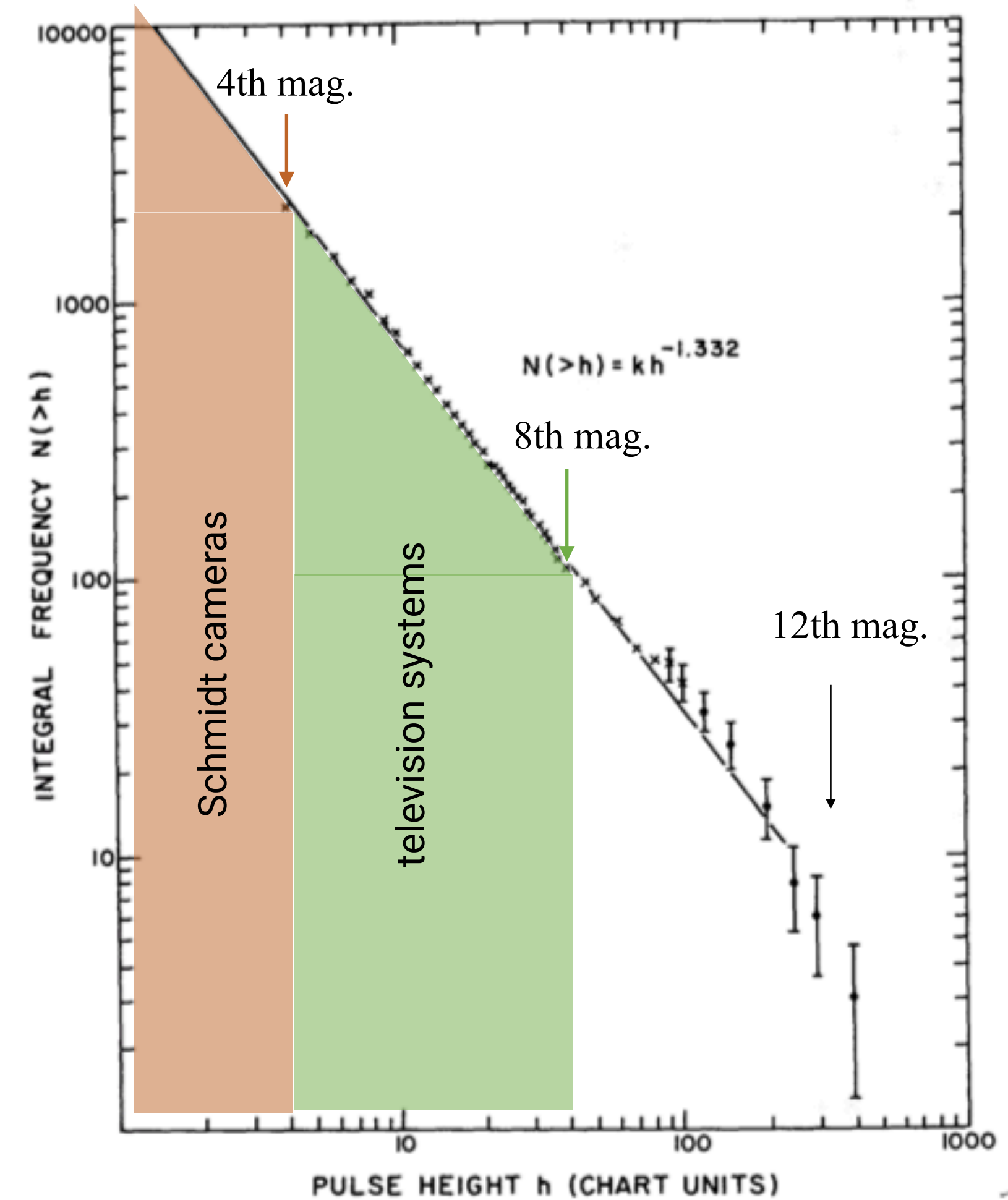
Figure 5. Integral pulse height distribution of all the recorded meteors in the detector channel A.

Cook et al. MNRAS 193, 645 (1980).

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Optical observations setting limits on DM candidates

Nuclearites—a novel form of cosmic radiation

A. De Rújula* & S. L. Glashow†‡

* Theory Division, CERN, CH-1211 Geneva 23, Switzerland
† Department of Physics, Boston University, Boston, Massachusetts 02215, USA

E. Witten (personal communication) has raised the intriguing possibility that nuclear matter consisting of aggregates of up, down and strange quarks in roughly equal proportions may be less massive than ordinary nuclear matter of the same quark number consisting of protons and neutrons (triplets of non-strange quarks). These nuggets of strange quark matter may be stable for almost any baryon number (A), including values intermediate between those of ordinary nuclei ($A \lesssim 263$) and neutron stars ($A \sim 10^{57}$). We use the term 'nuclearite' to describe such strange quark nuggets in collision with Earth and suggest experiments to detect these encounters.

Ordinary nuclear matter has an energy density of ~938 MeV per nucleon. Ordinary quark matter—a purely hypothetical form of matter in which the constituent up and down quarks and gluons are not confined within individual nucleons—evidently has a higher energy density, for otherwise nuclei would decay into quark matter. Strange quark matter (consisting of equal numbers of up, down and strange quarks) differs energetically from ordinary quark matter in two ways: strange quarks are considerably heavier than ordinary quarks, which is why strange baryons are some 200 MeV heavier than nucleons. On the other hand, the Pauli exclusion principle acts so as to make strange quark matter more stable than ordinary quark matter. In a degenerate gas of massless quarks at zero temperature, the energy per quark depends on the number of quark species, and in a three-flavour system (strange quark matter) it is estimated by Witten to be ~90% of what it is in a two-flavour system.
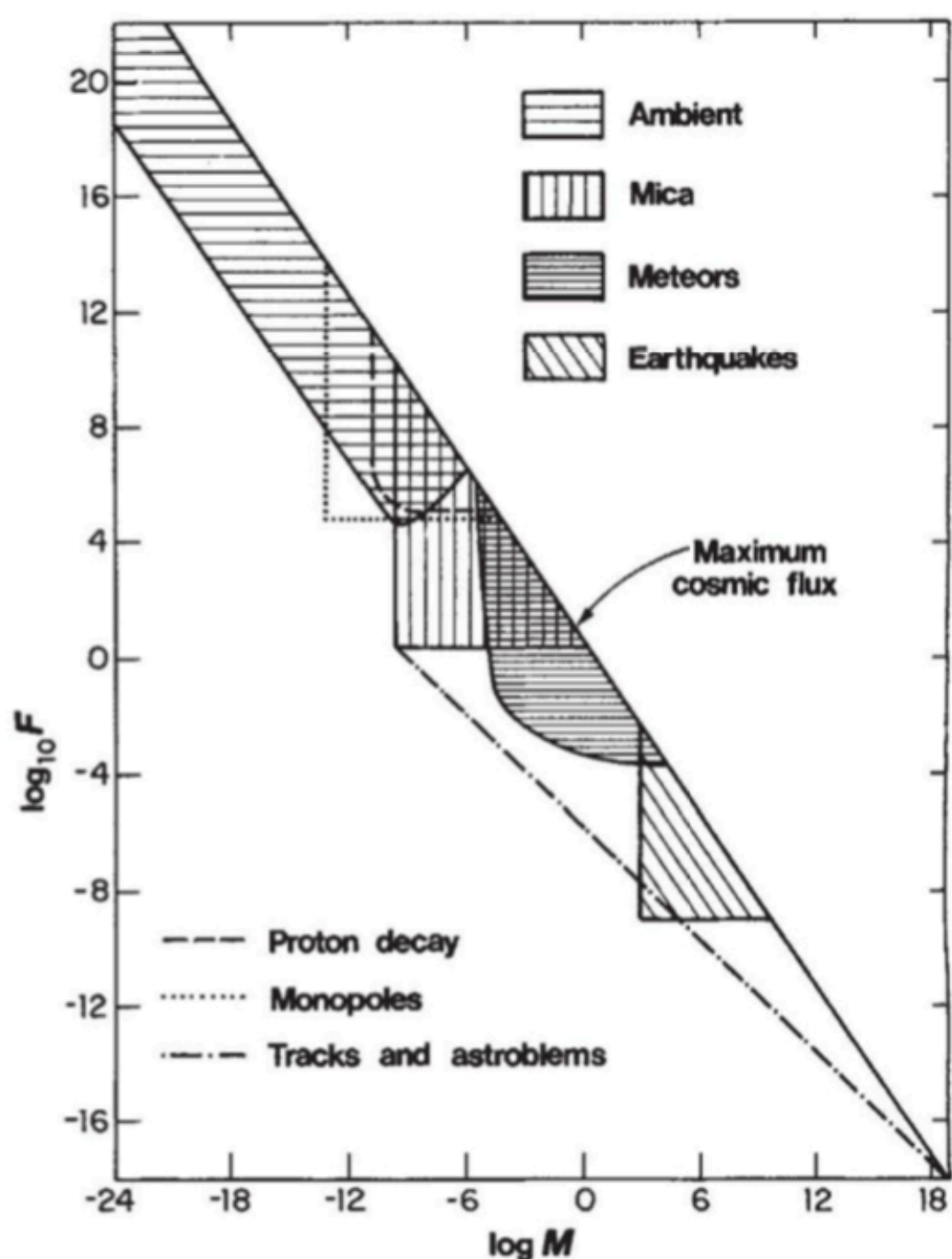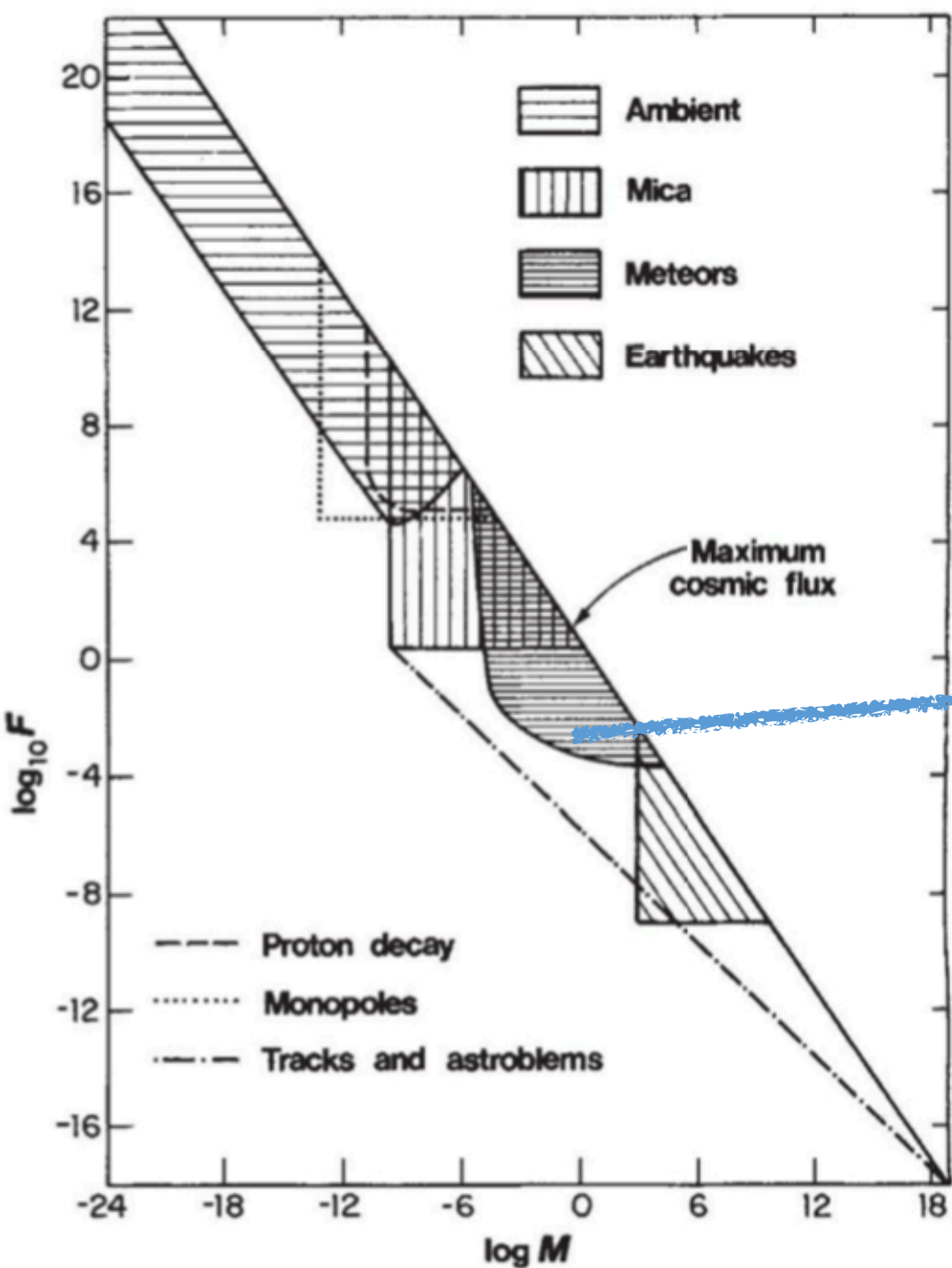

Fig. 1 The maximum possible cosmic flux of nuclearites F ($km^{-2} yr^{-1} (2\pi sr)^{-1}$) as a function of mass. Also shown are regions that would be excluded by the several experiments discussed in the text. (Of these, only the 'mica' limit corresponds to an experiment actually performed.)

De Rújula & Glashow (1984)

- Aggregates of up, down, strange quarks formed at early epoch
  ➡ Dark Matter candidate

- Surrounded by electron 'shield'
  ➡ ∴ electrically neutral

- passage through atmosphere causes light much like a meteorite

- but travelling at galactic velocities (~270km/s, c.f. meteorites 12-72 km/s)

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Optical observations setting limits on DM candidates

LETTERS TO NATURE

Nuclearites—a novel form of cosmic radiation

A. De Rújula* & S. L. Glashow†‡

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† Department of Physics, Boston University, Boston, Massachusetts 02215, USA

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De Rújula & Glashow (1984)

NATURE VOL. 316 4 JULY 1985 — LETTERS TO NATURE

A search for evidence of nuclearites in astrophysical pulse experiments

N. A. Porter*, D. J. Fegan*, G. C. MacNeill* & T. C. Weekes†

* Physics Department, University College, Dublin 4, Ireland
† Harvard-Smithsonian Center for Astrophysics, Whipple Observatory, Arizona 85645-0097, USA

De Rújula and Glashow[1] have suggested that nuclearites, aggregates of up, down and strange quarks in roughly equal proportions, may form a component of the material reaching the Earth from the Galaxy. On traversing the atmosphere they will look something like meteors, but will travel faster. The masses of these aggregates may vary over a wide range and their velocities will be typically 250 km s^{-1}, corresponding to the Sun's galactic rotation. If all the dark matter in the Galaxy is assumed to be in the form of nuclearites, a limit can be set to the incoming flux. We report here upper limits derived from four experiments, originally carried out to detect cosmic γ rays, as well as some derived by other authors, which would be sensitive to pulses of light from nuclearites in the lower atmosphere. Our upper limits are compatible with the suggested maximum flux and competitive with a search for tracks etched in mica[2], which could also be caused by nuclearites.

De Rújula and Glashow show that the visual magnitude of an atmospheric nuclearite:

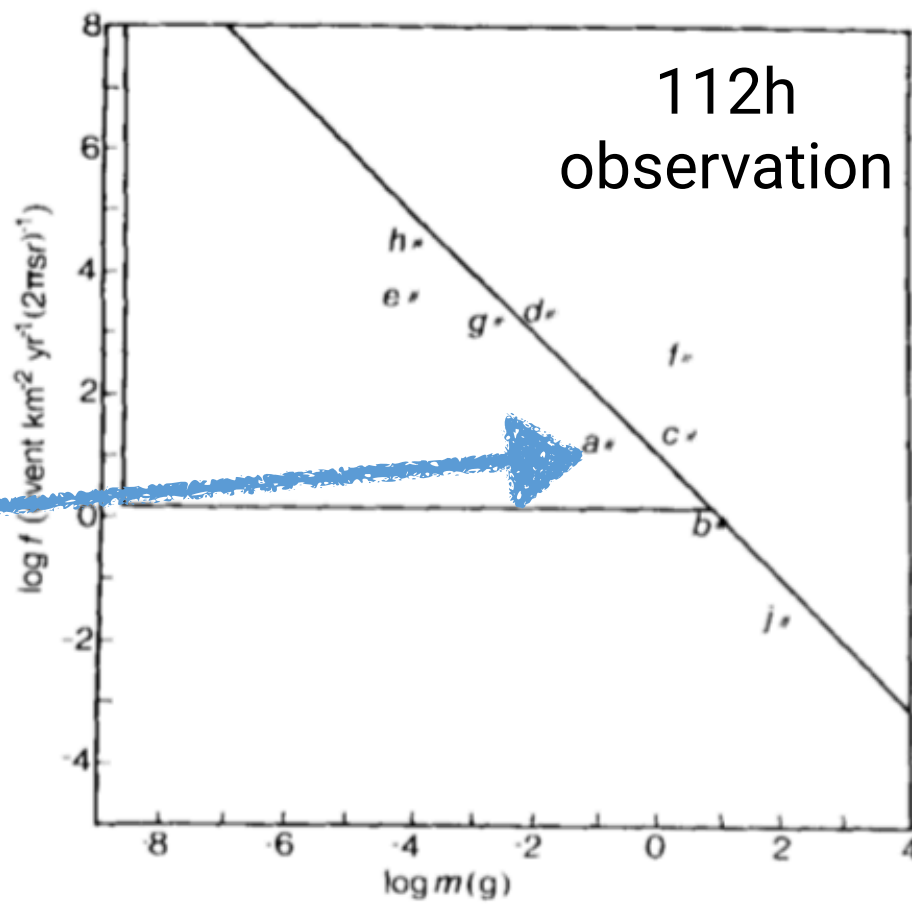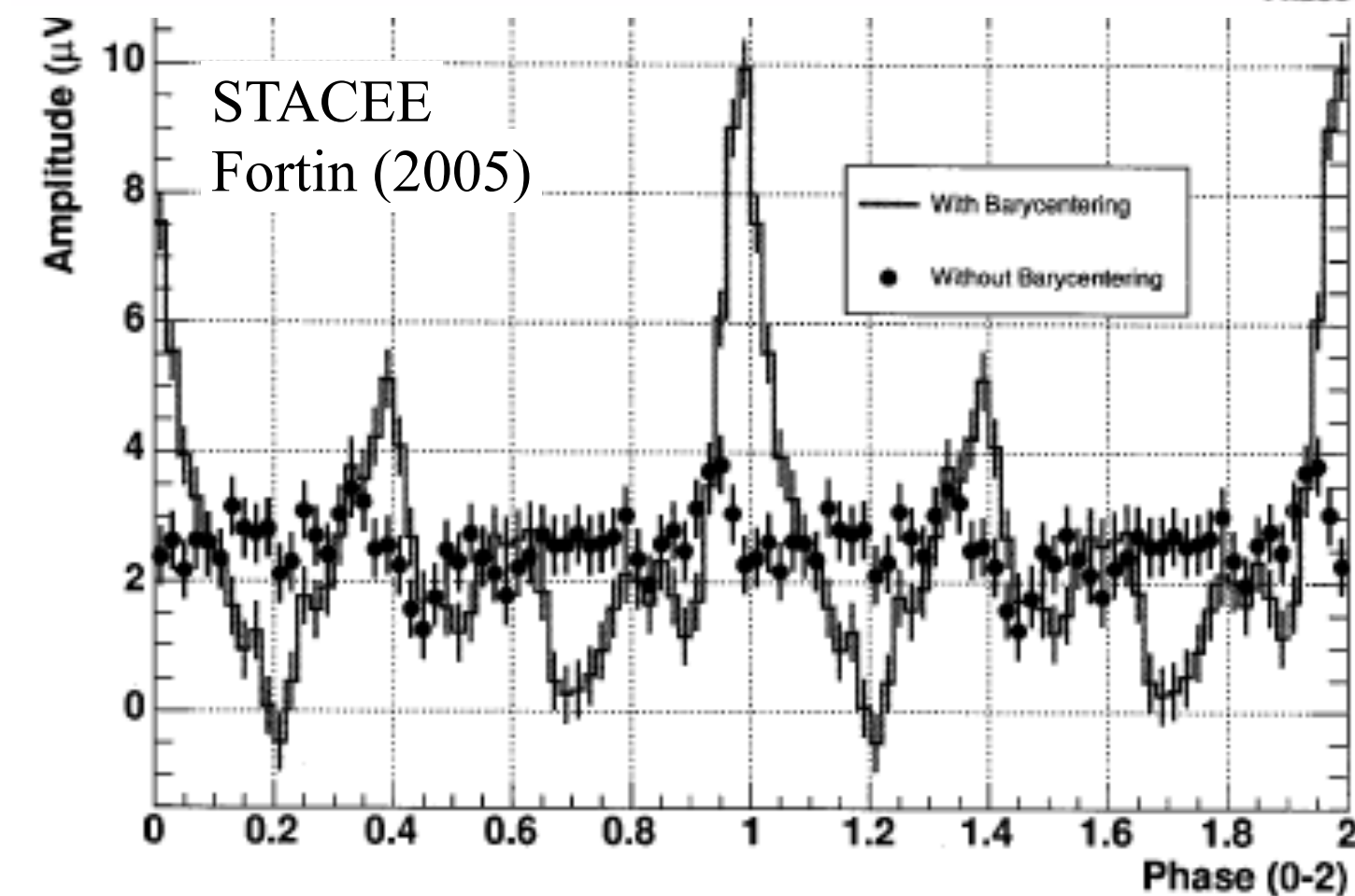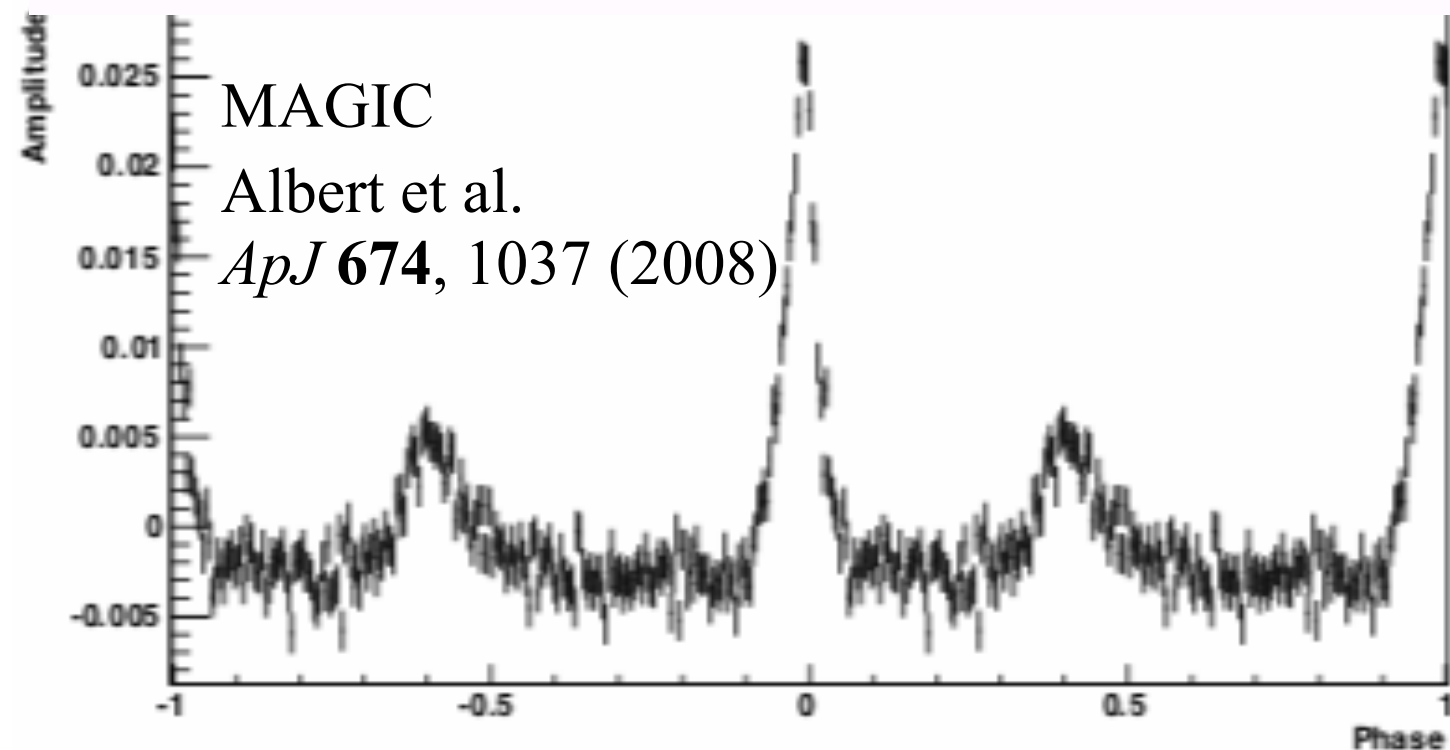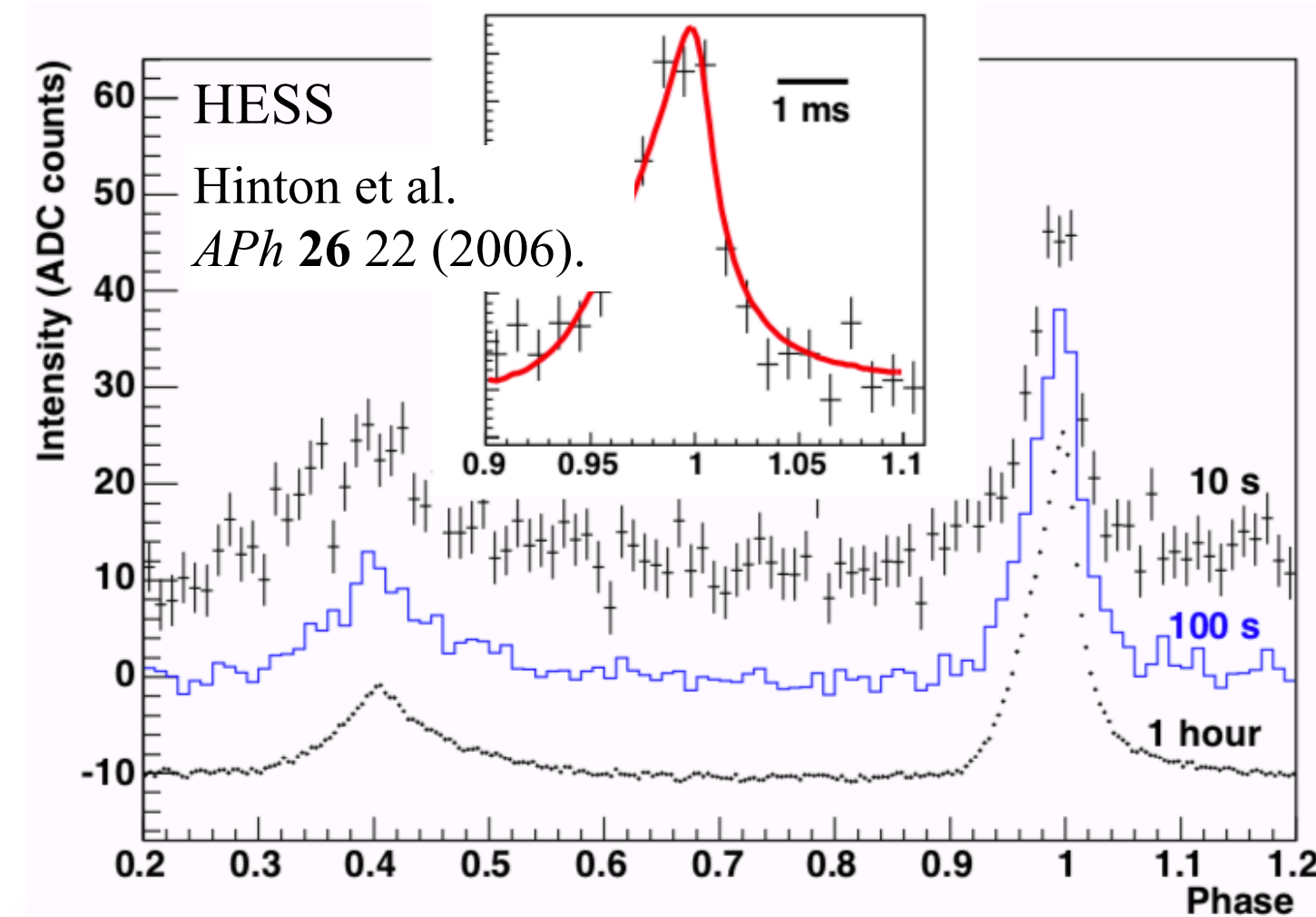$$M = 10.8 - 1.67 \log_{10}(m/10^{-6}) + 5 \log_{10}(h/10 \text{ km}) \quad (1)$$

plier, we obtain a photon number of 823 photons in 10^{-8} s average illumination over the 10^{-2} s transit time. The area of the reflector was effectively 60 m^2, leading to a flux of 1.37×10^{-3} photons cm^{-2} in 10^{-8} s, or 1.37×10^5 photons cm^{-2} s^{-1}. Converting this to erg cm^{-2} s^{-1} to obtain the visual magnitude[6] and taking 0 mag = 8.5×10^{-6} erg cm^{-2} s^{-1}, we obtain a limiting mag-

112h observation

Fig. 1 Mass of the nuclearites plotted against incoming flux. The sources are detailed in Table 1.

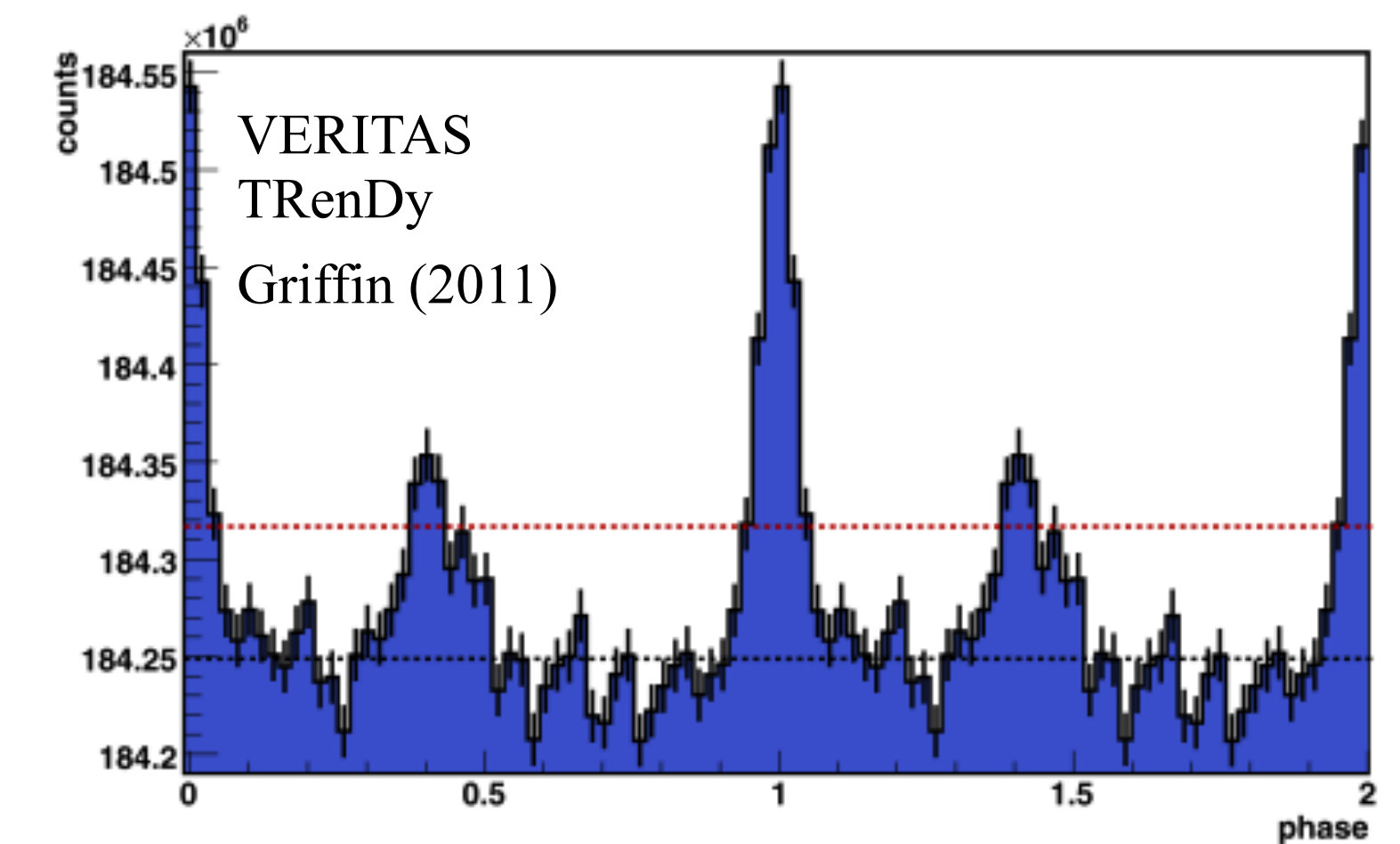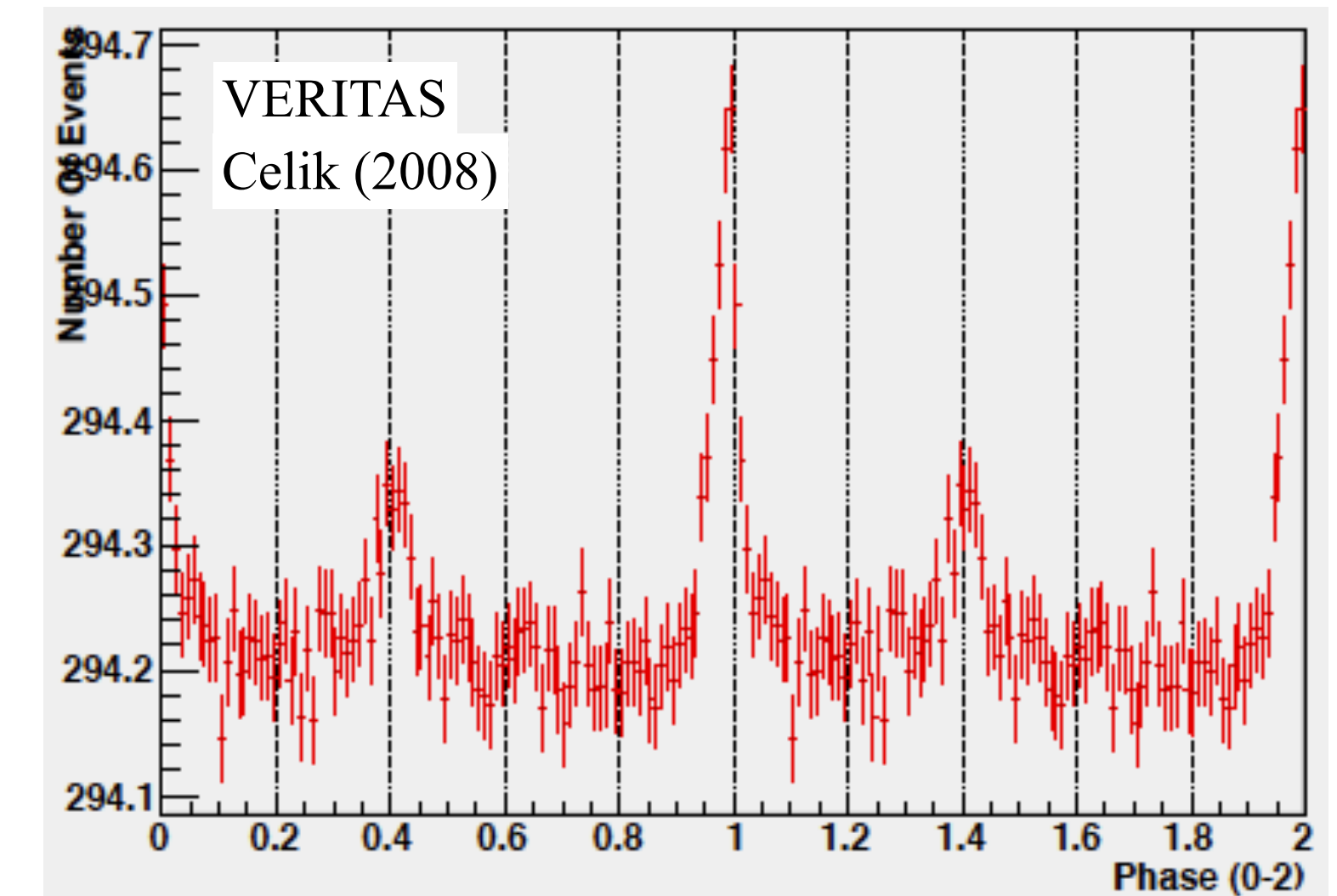Porter et al.(1985)

Signature is like a meteor, but travels at galactic velocities (~270 km/s) instead of solar system (12-72 km/s)

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Whipple 10m
Srinivasan et al.(1997)
S/N ~ 0.0003

HEGRA CT1
Oña Wilhelmi et al.
APh **22**, 95 (2004)

Celeste
de Naurois et al.
ApJ **566**, 343 (2002)

Optical Phase Histogram

HESS
Hinton et al.
APh **26** 22 (2006).

1 ms

10 s
100 s
1 hour

MAGIC
Albert et al.
ApJ **674**, 1037 (2008)

STACEE
Fortin (2005)

With Barycentering
Without Barycentering
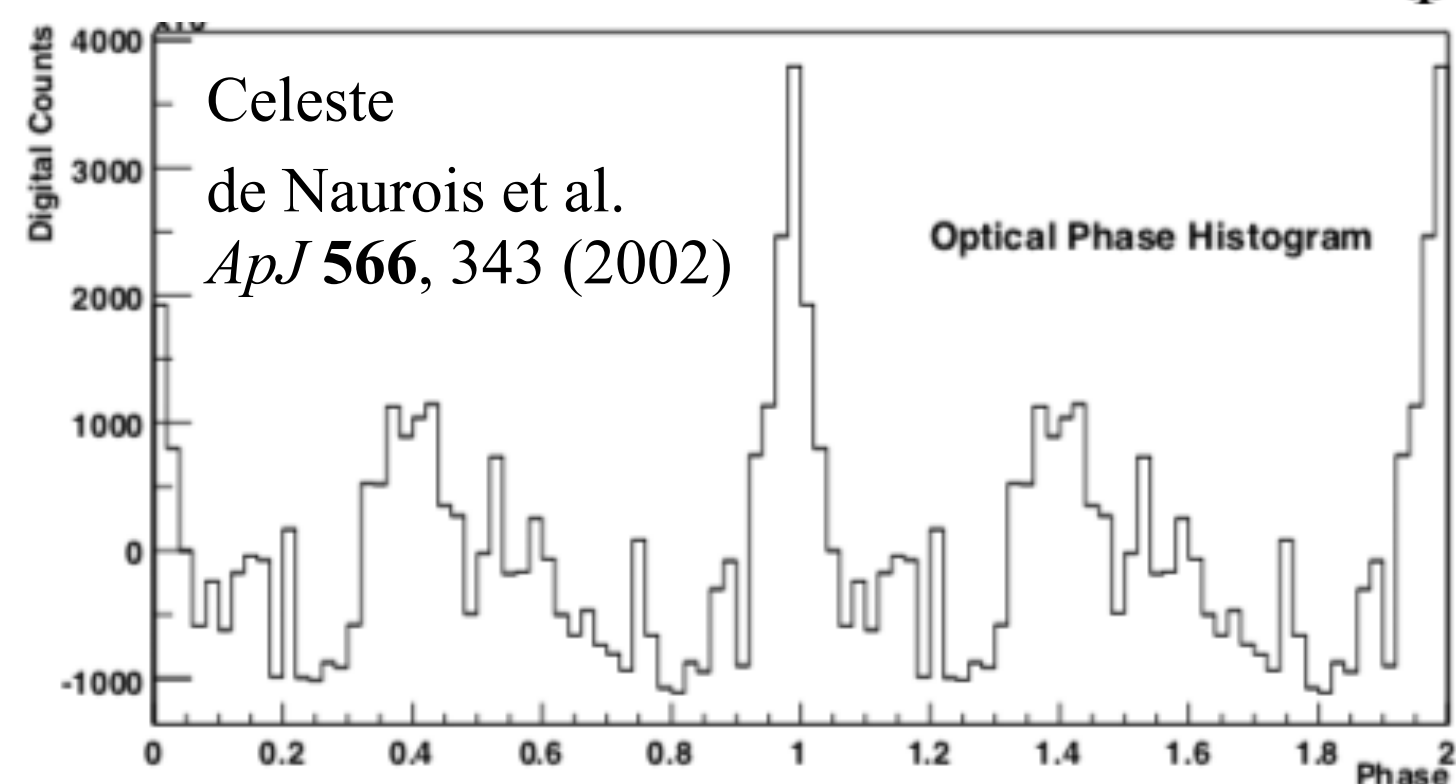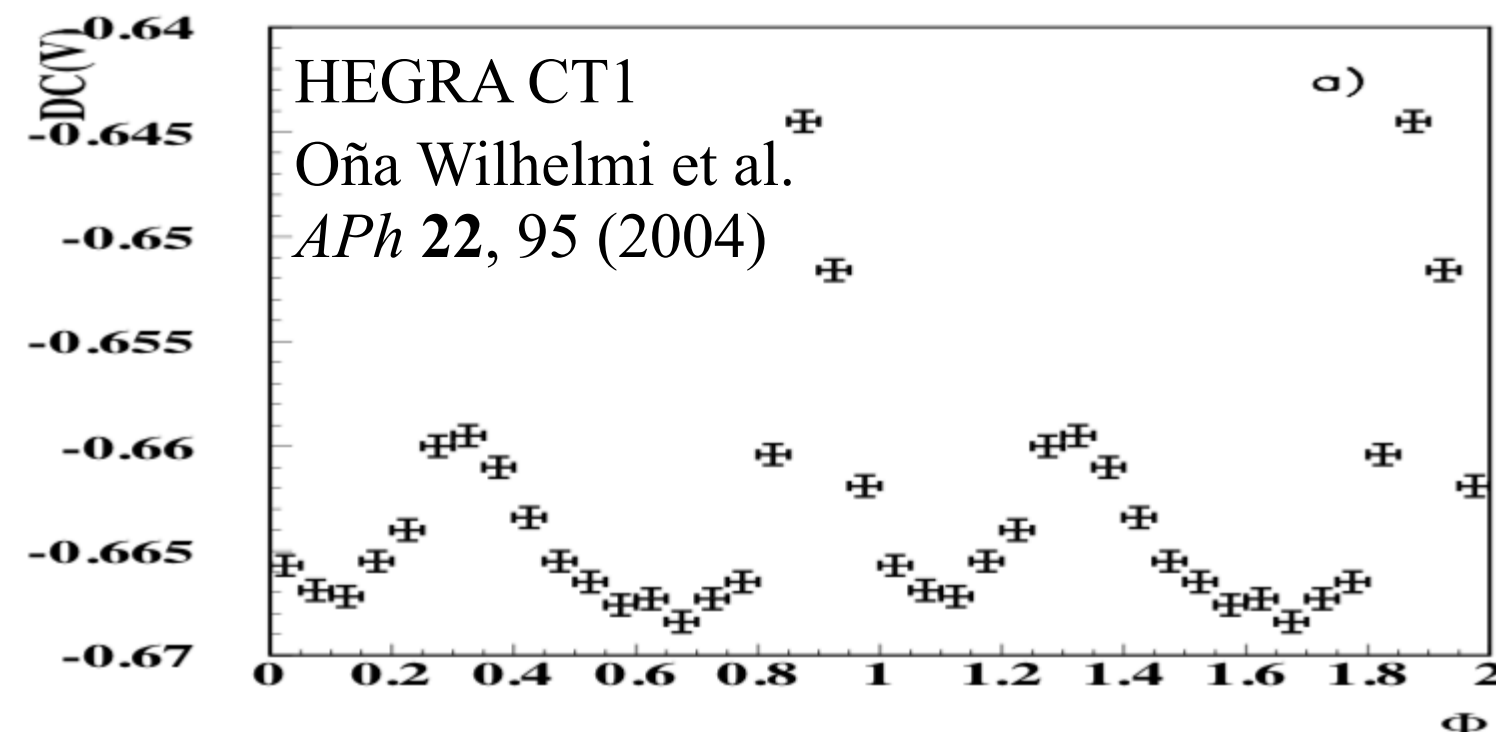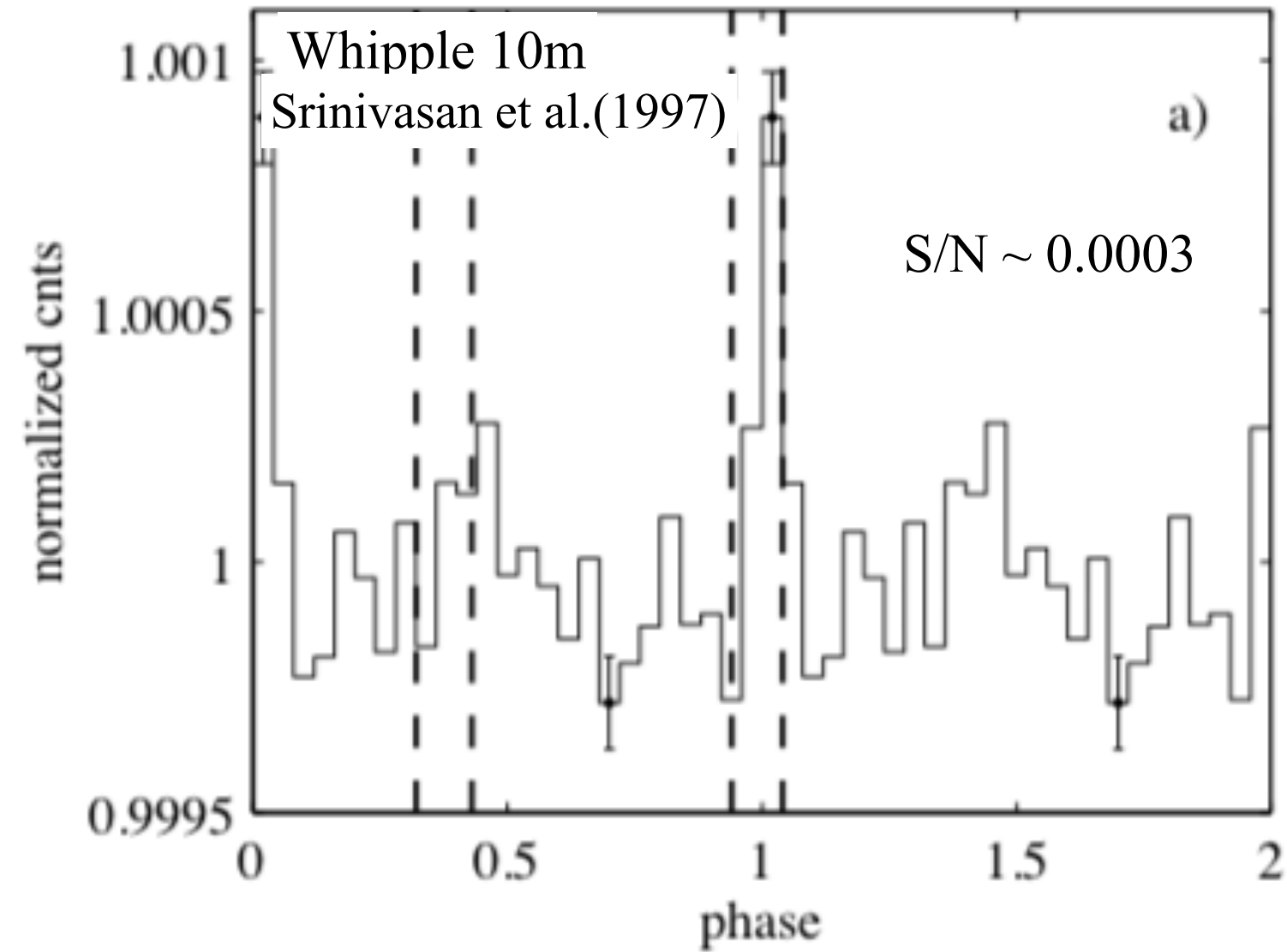
Periodically IACTs measure the Crab optical pulsar to verify their timing analyses…

VERITAS
Celik (2008)

VERITAS
TRenDy
Griffin (2011)

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High Time Resolution Optical Photometry

Whipple 10m (1974)

Flux of optical meteors — 647
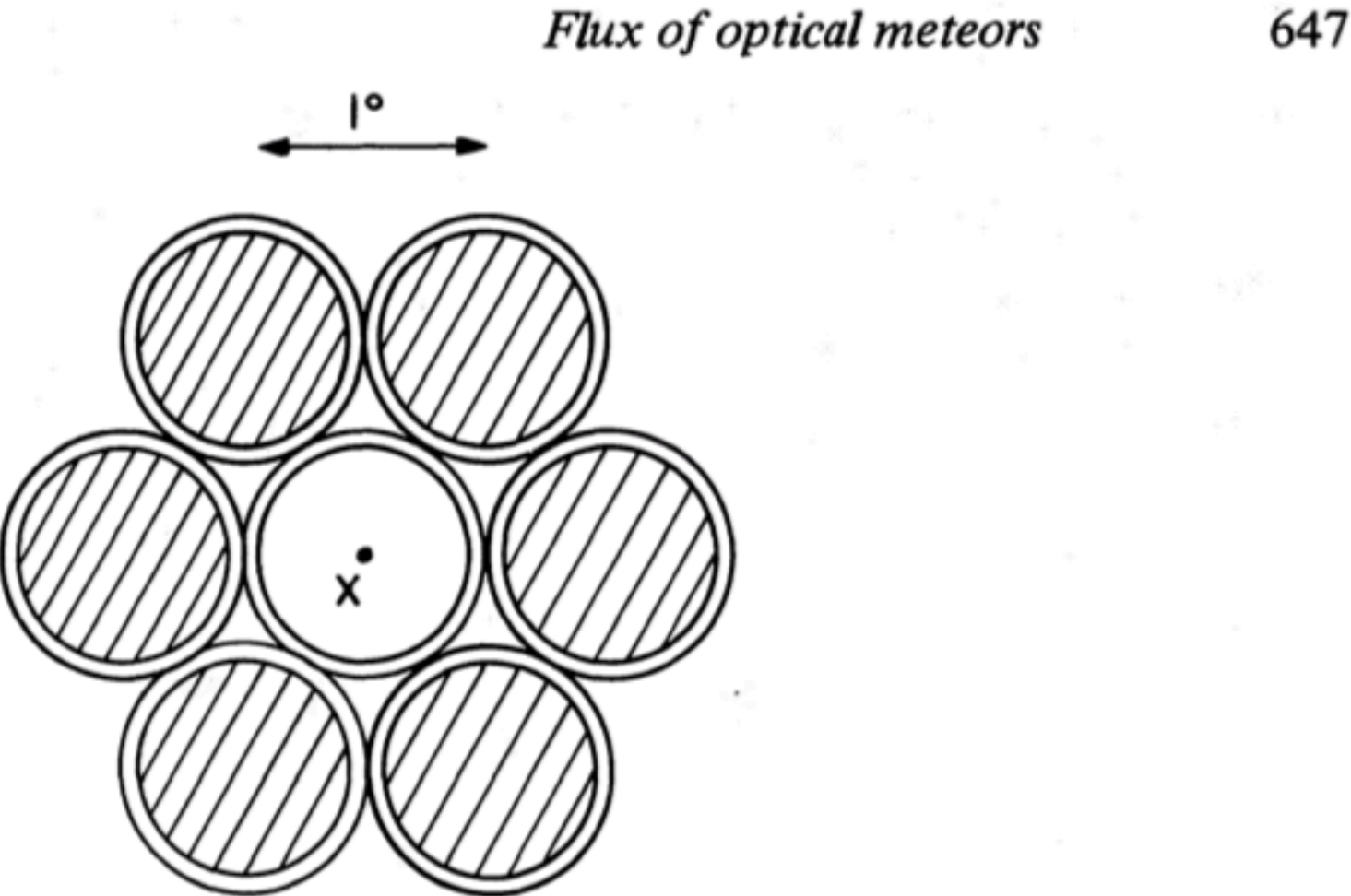
Figure 1. Phototube configuration at focal point of the 10-m reflector. X = detector. Separation between tube centres is 1°.2. Cross-hatched areas are covered by guard ring.
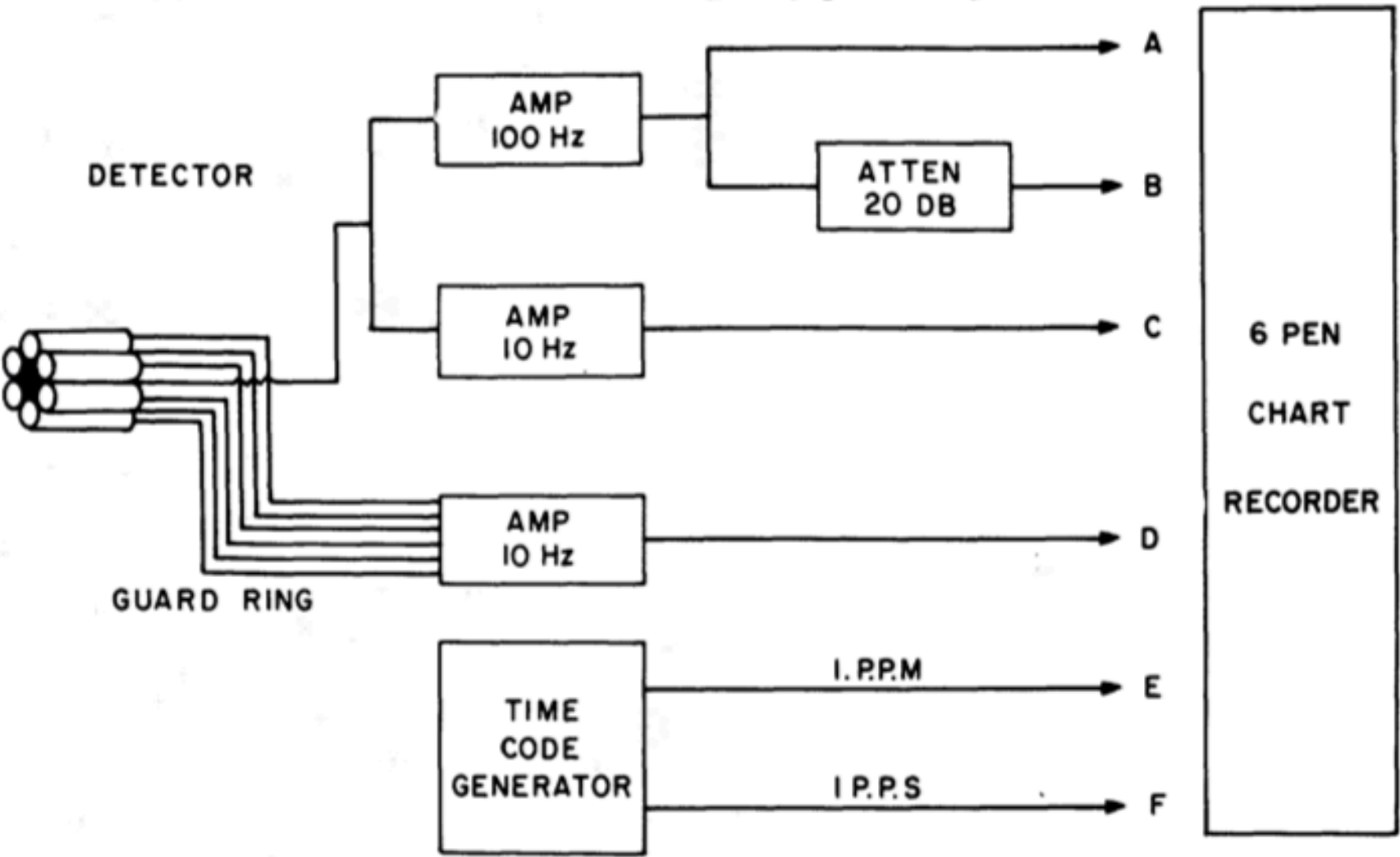
Figure 2. Block diagram of recording system.

Cook et al. *MNRAS* **193**, 645 (1980).
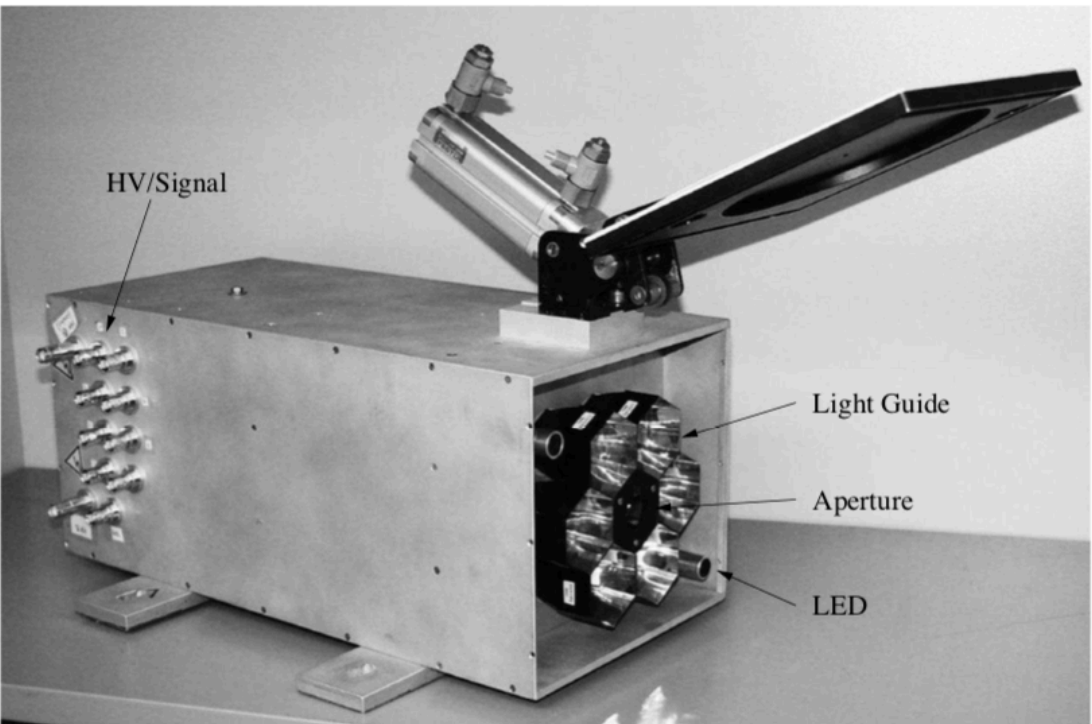
Fig. 1. Photograph showing the principle mechanical components of the optical pulsar camera: the central pixel aperture, the "veto" pixel light guides, the positioning LEDs and the HV inputs/signal outputs for the photomultipliers mounted within the casing. Hinton et al. *APh* **26**, 22 (2006).
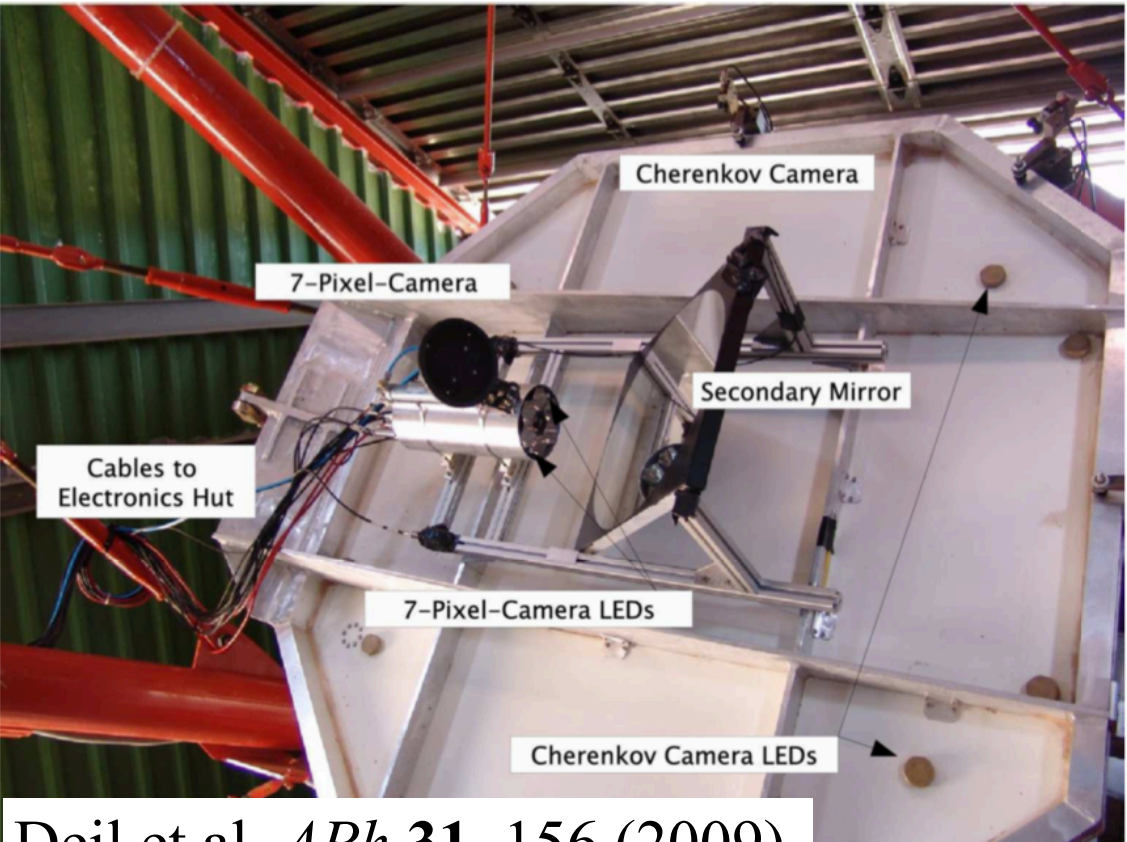
Deil et al. *APh* **31**, 156 (2009).
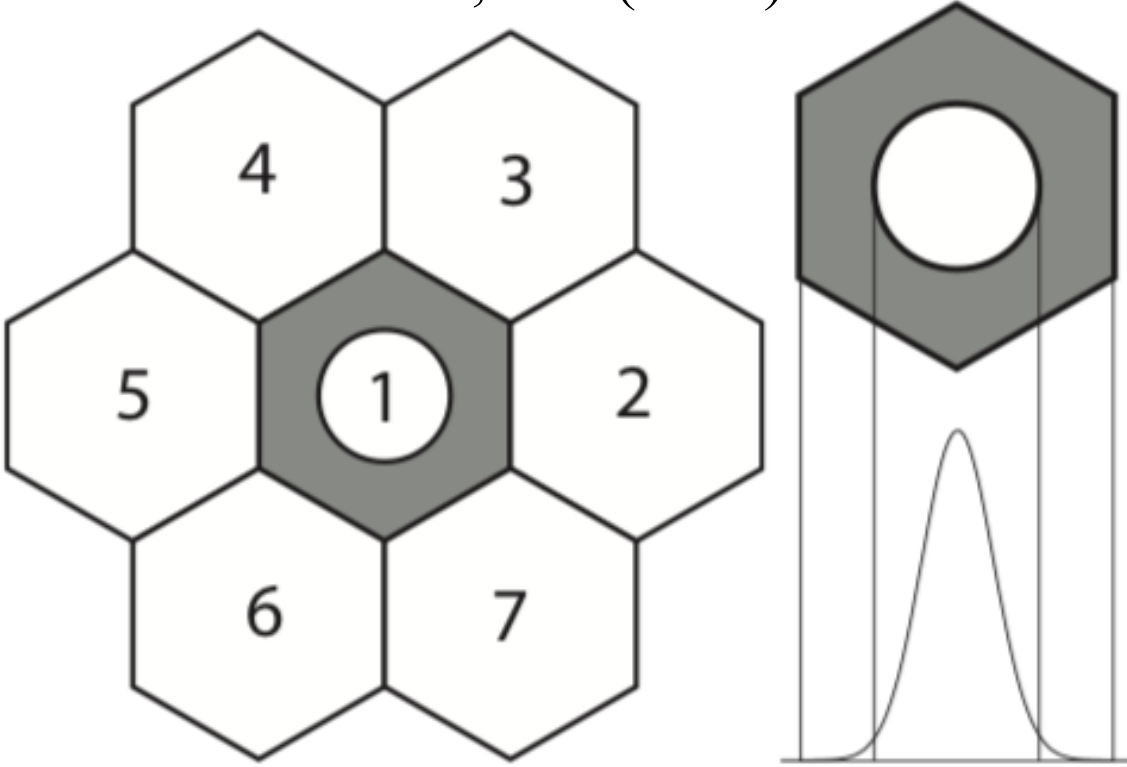
It is a matter of preference as to whether the photodetector is internal or external to the Cherenkov camera, the technology is largely the same, it is just the integration time that varies based on the science case

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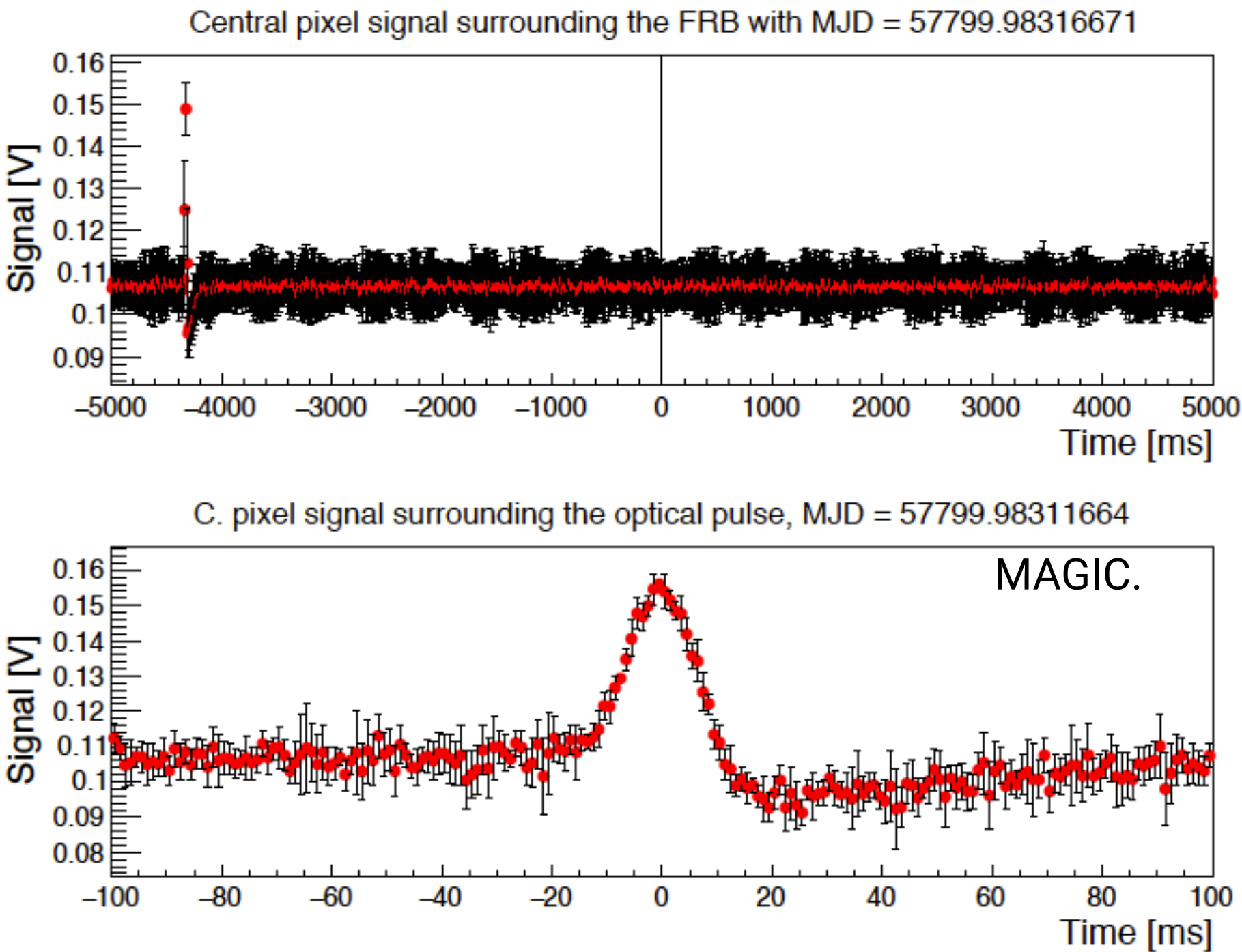# But mostly it may have felt like meteors are what is mostly (only) seen…
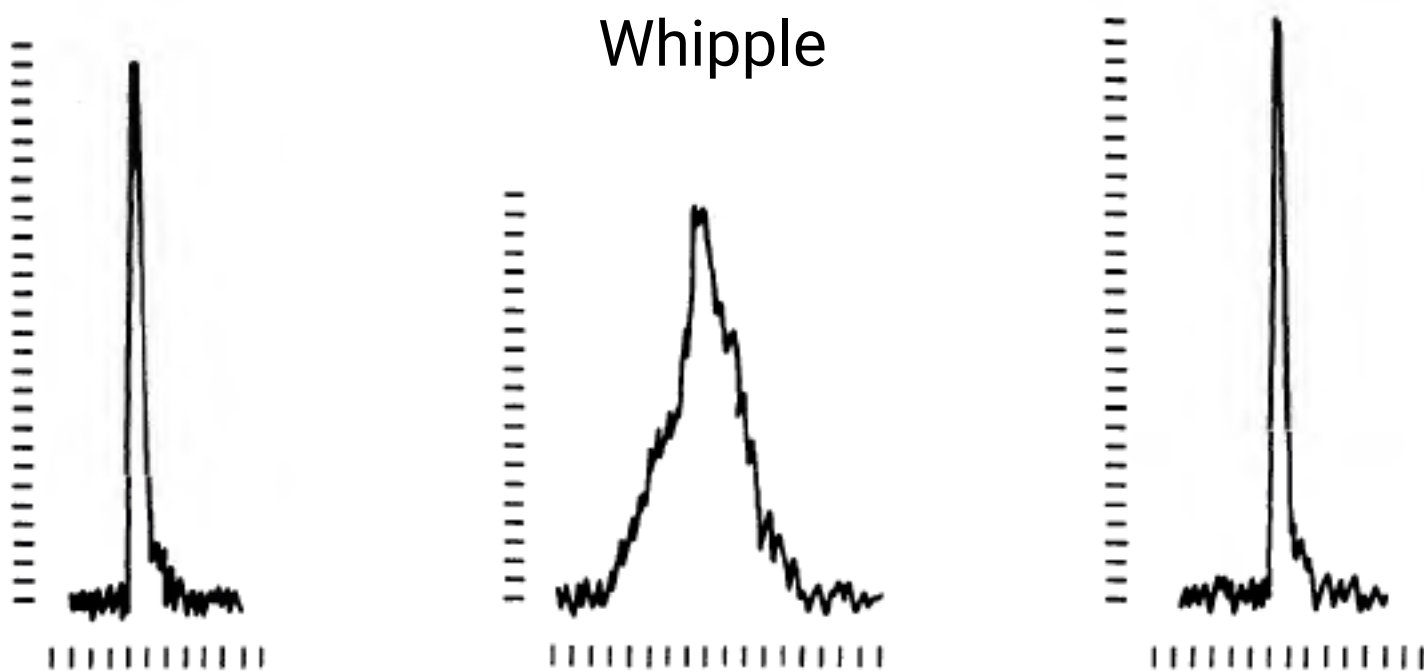
Whipple
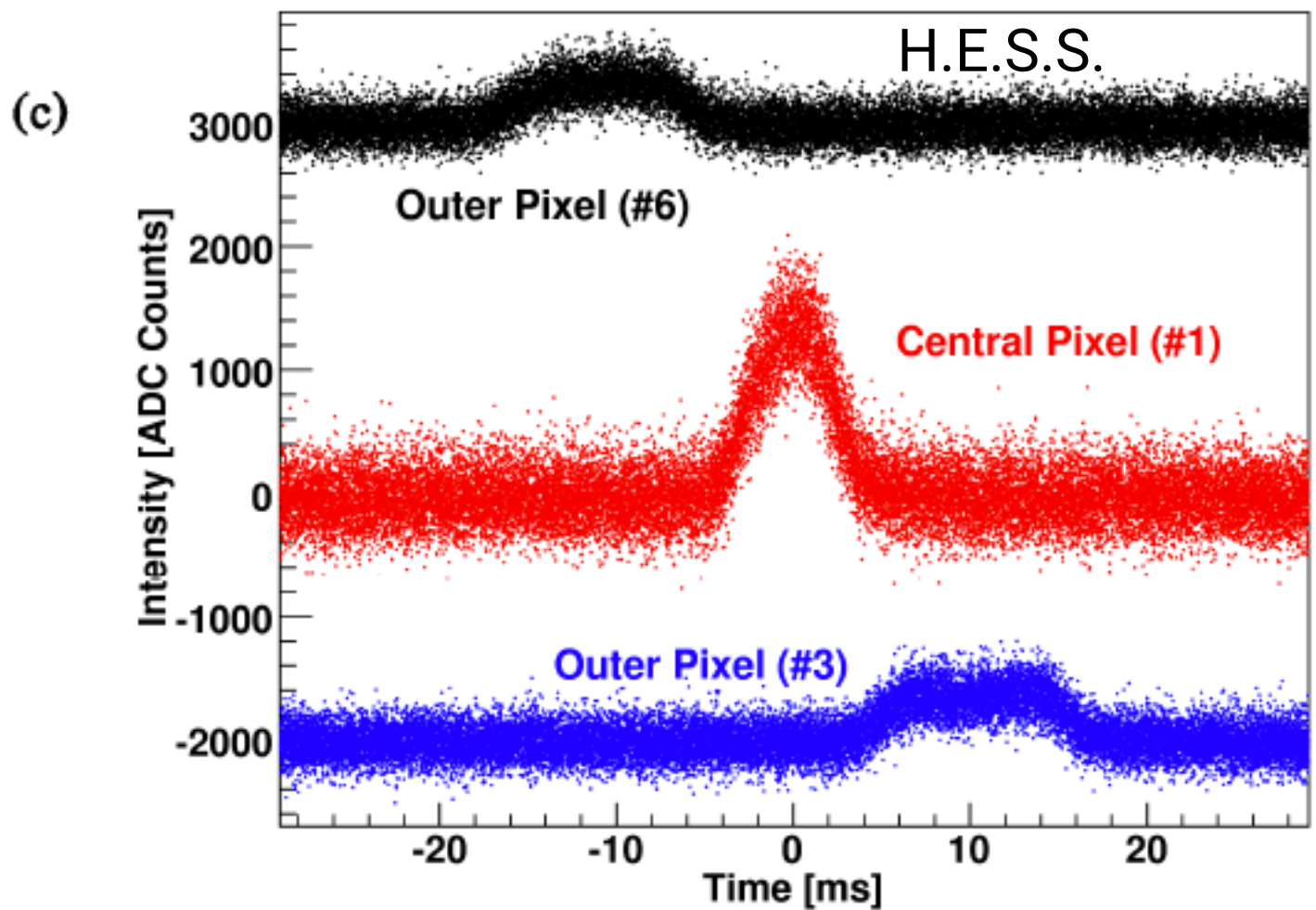
Fig. 5. Example background events very likely caused by a shooting star (*top*) and lightning (*bottom*). The intensities were arbitrarily offset such that the light curves from different channels do not overlap.
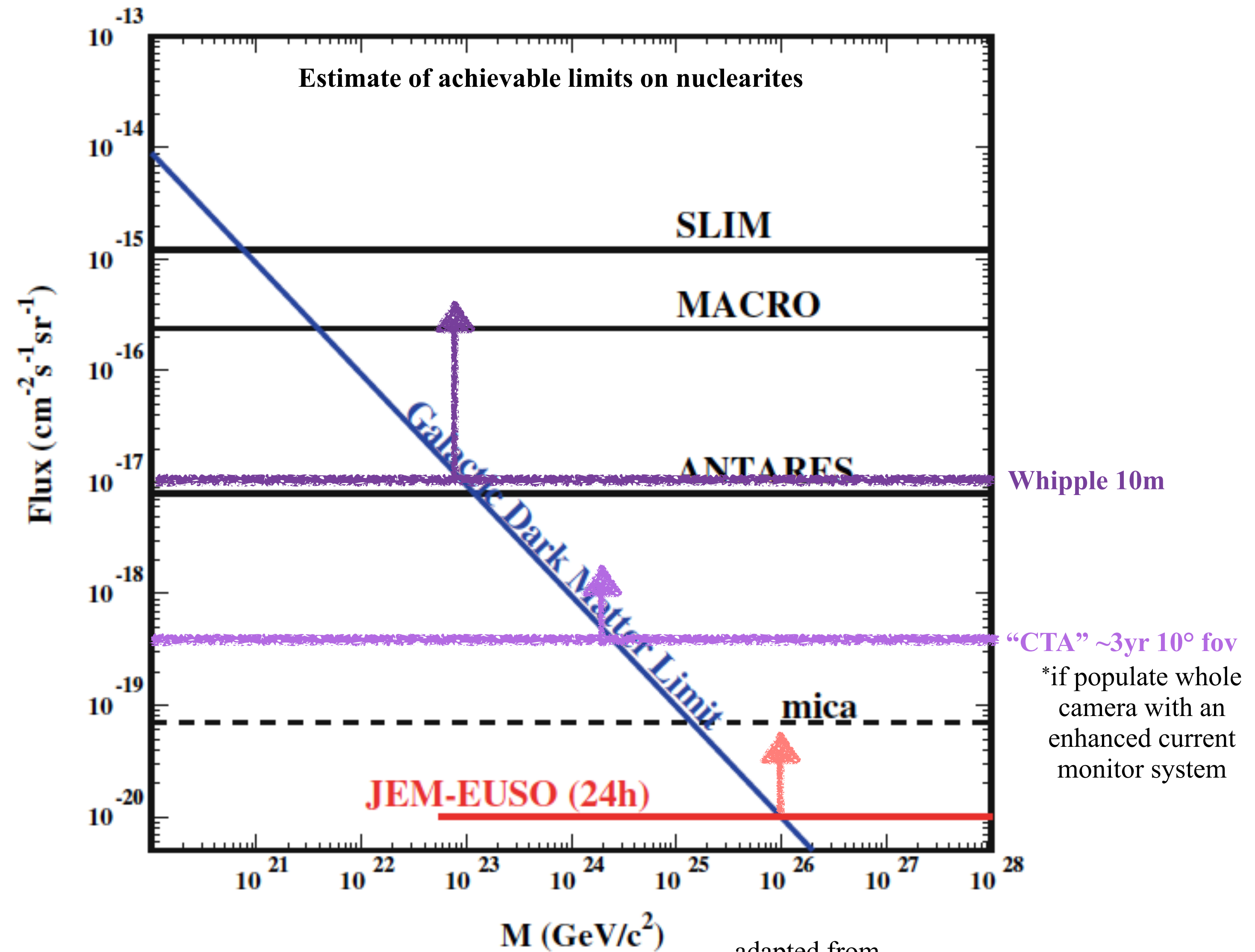
Figure 3. *Top*: Optical light curve covering 10 s around the first FRB in our sample, for an integration window of 10 ms. A clear optical pulse is detected 4.3 s before the FRB. *Bottom*: Optical light curve covering 200 ms around the detected optical pulse, for an integration window of 1 ms. The pulse is consistent with a background event. Note that the undershoot after the optical flash is caused by the central pixel readout electronics.

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An aside on FoV

BTW, the more of the field of view you populate, the more you can do.

Estimate of achievable limits on nuclearites

adapted from
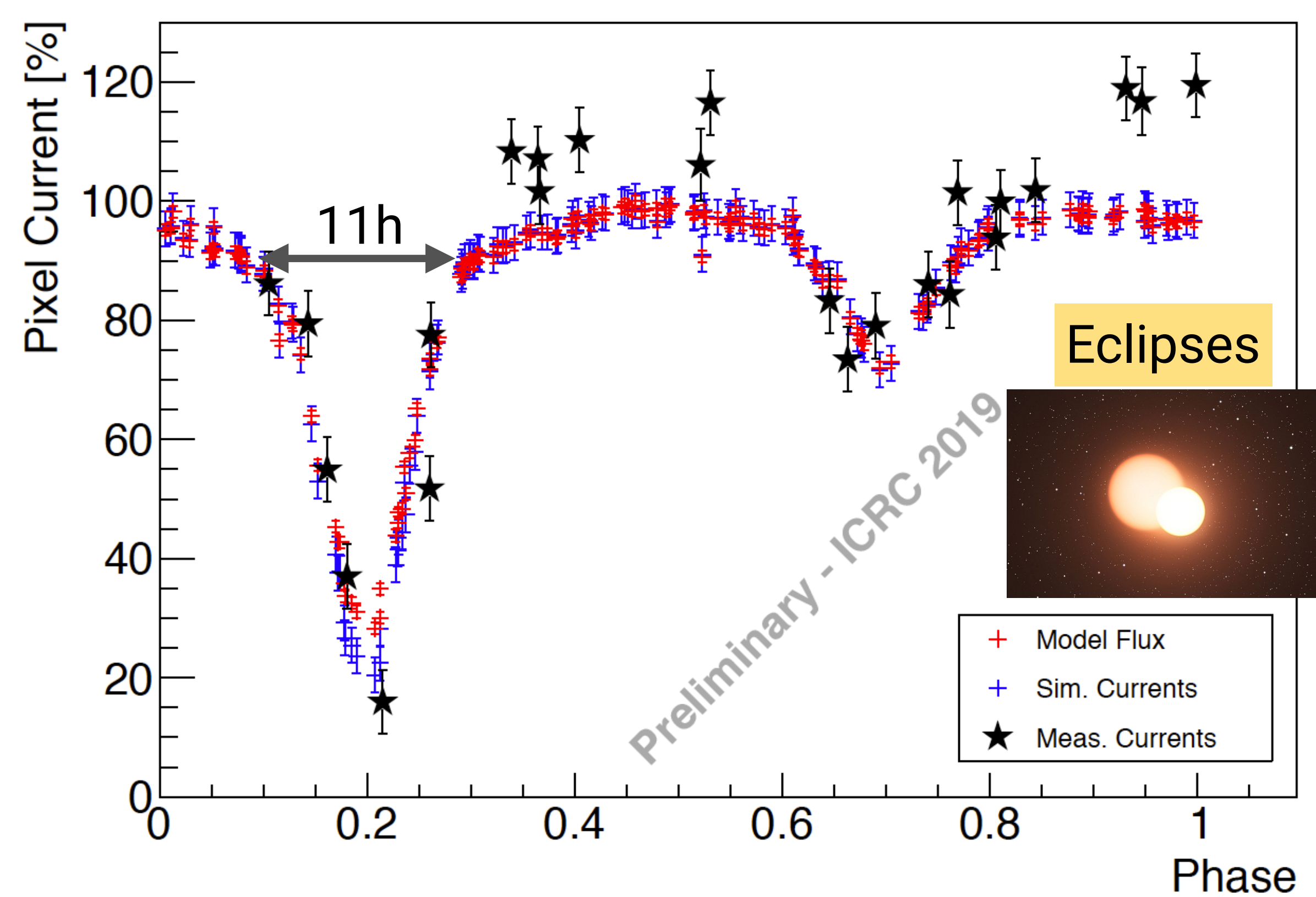JEM-EUSO: Meteor and nuclearite observations
Adams et al. *ExA* **40**, 253 (2015)

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PLATO'S ALLEGORY OF THE CAVE

Ascent to Sunlight

Fire

Diffused Sunlight

Shadows cast on wall

Roadway where puppet showmen perform

Prisoners
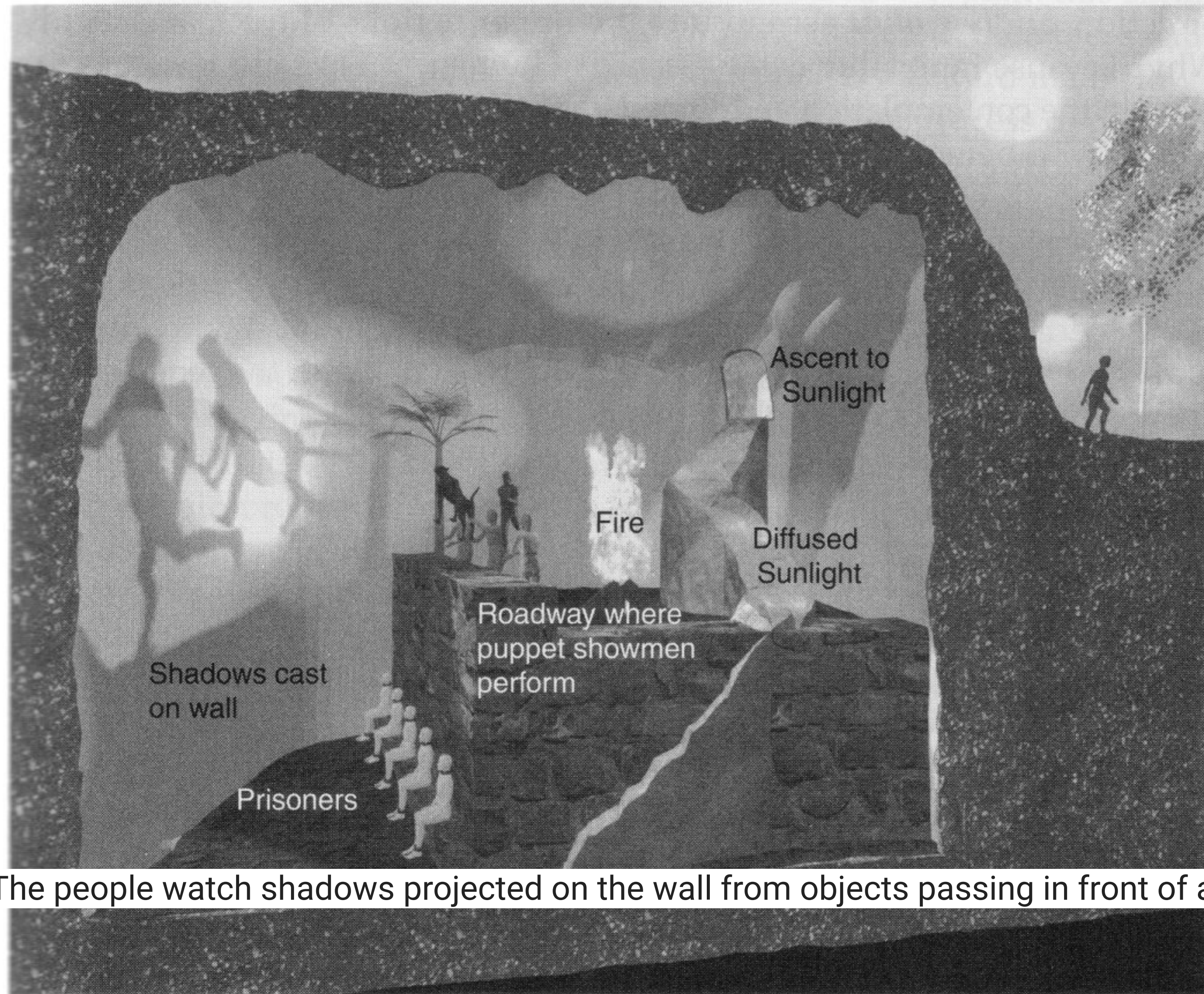
The people watch shadows projected on the wall from objects passing in front of a fire

L. Kreidberg

00 hours

Brightness

Time

L. Kreidberg
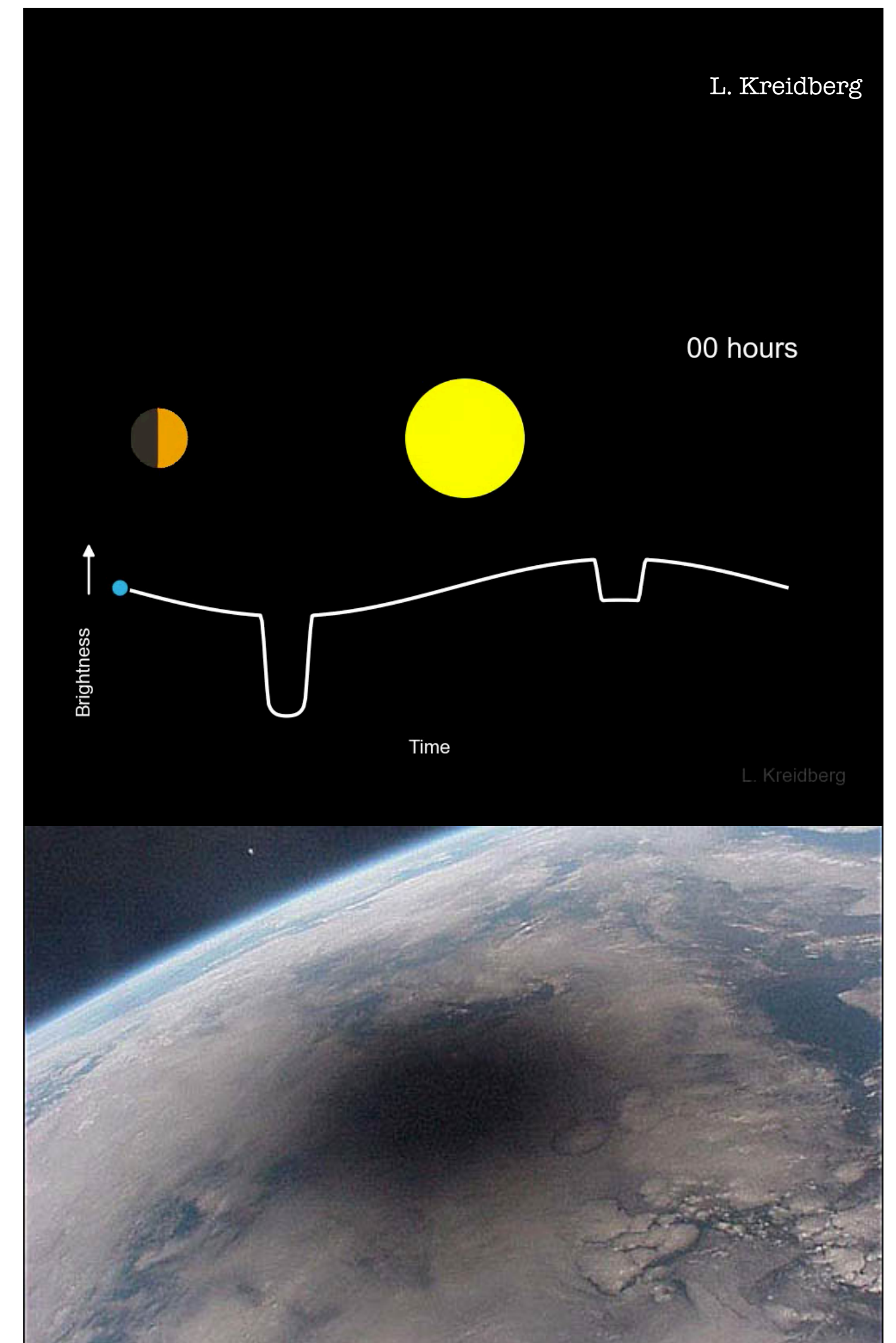
and give names to these shadows

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Eclipses

Transits

CAAT Data Sim

2h

11h

Model Flux
Sim. Currents
Meas. Currents

Preliminary - ICRC 2019

Occultations

4s
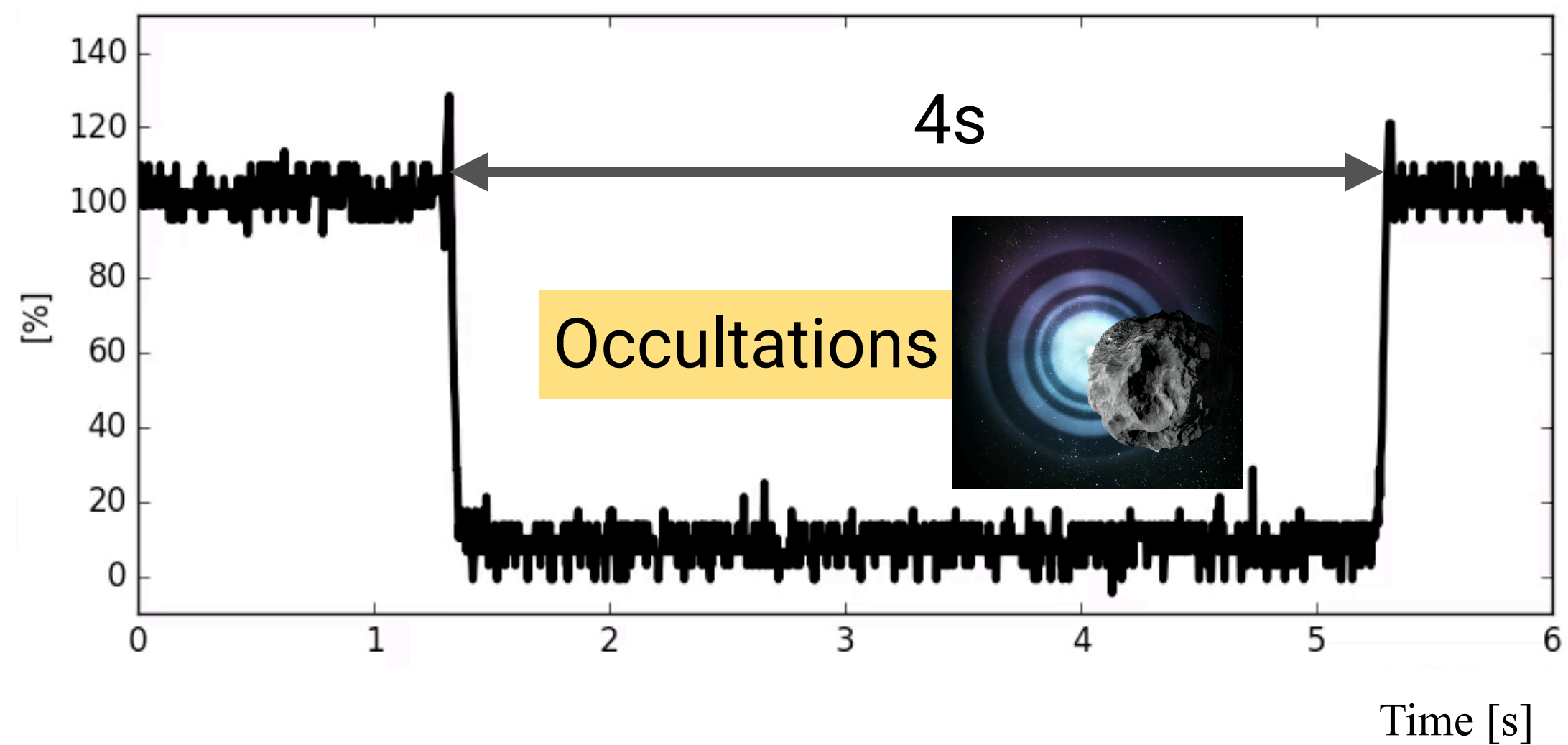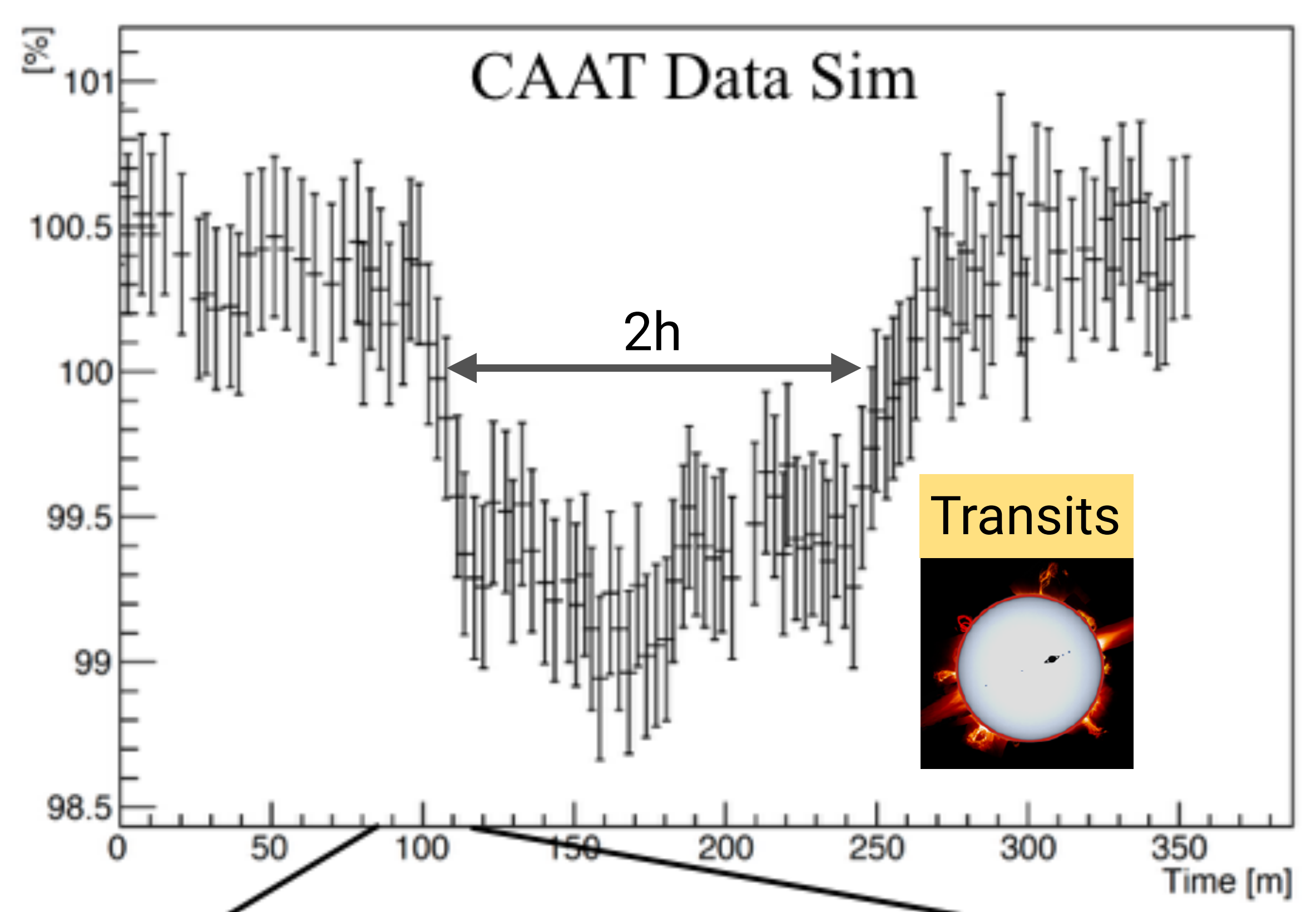
When it comes to predictable, testable outcomes its hard to beat passing something in front of a star.

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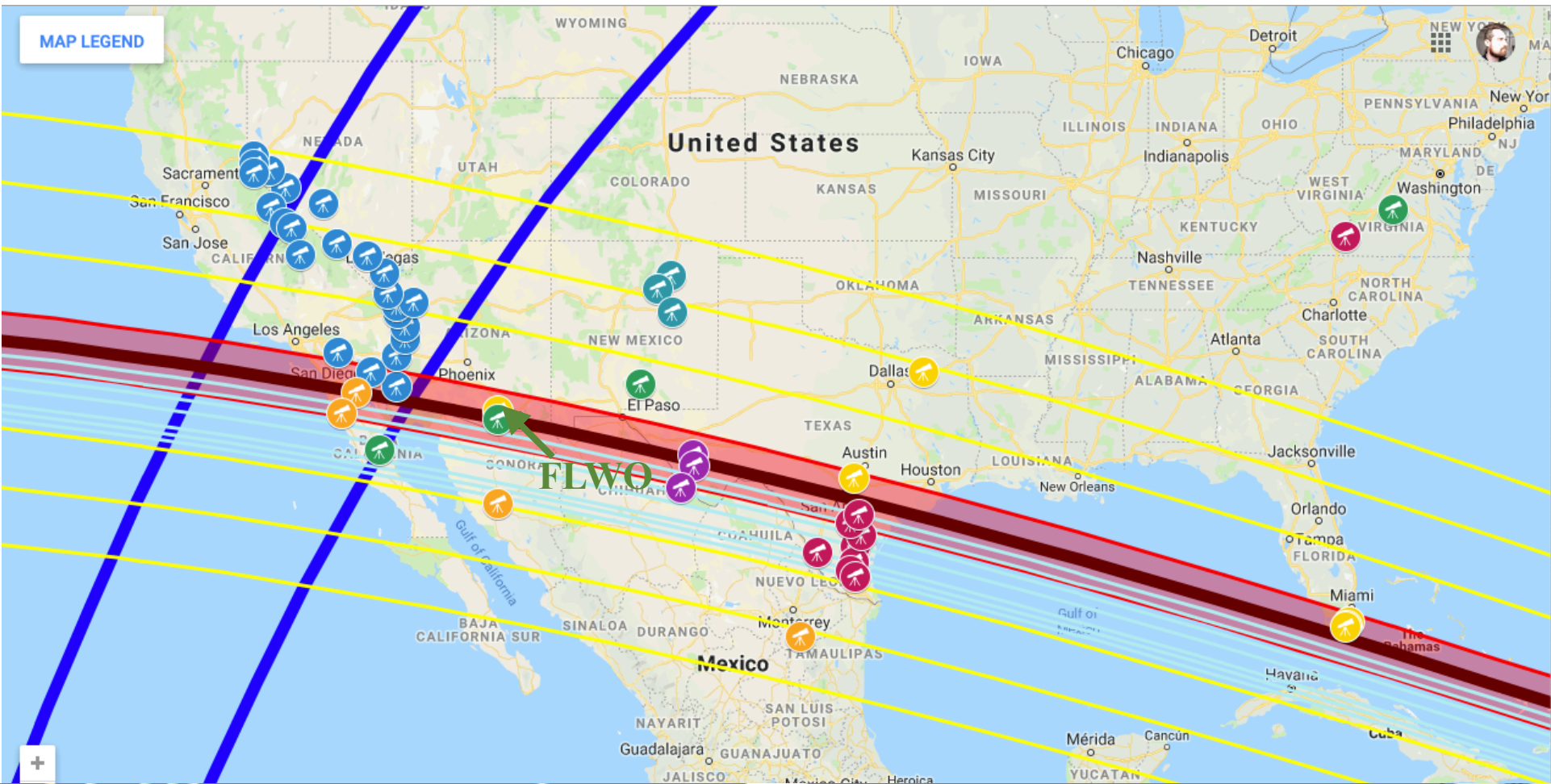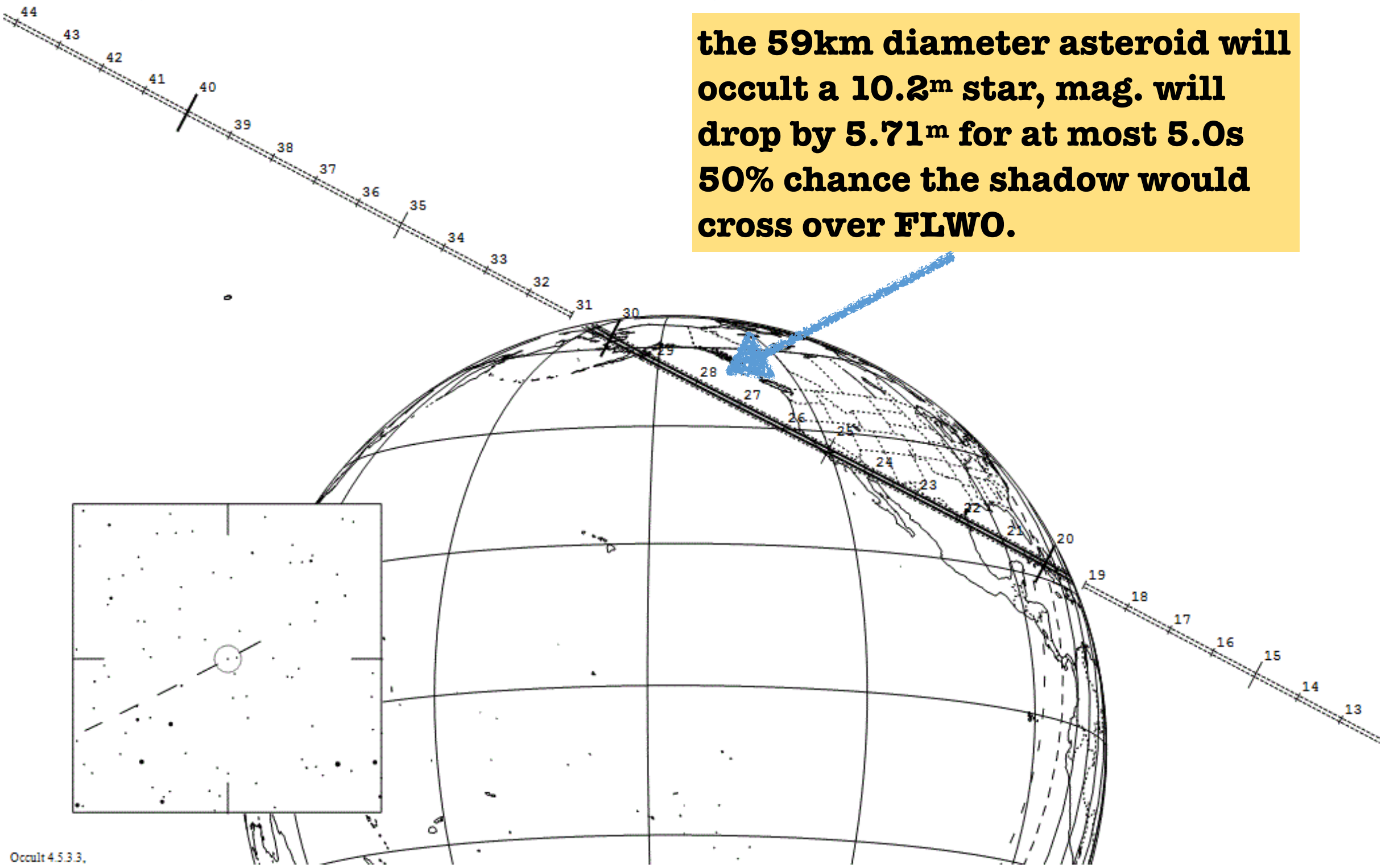HARVARD & SMITHSONIAN

(1165) Imprinetta / TYC 5517-227-1 occultation


```
1165 Imprinetta** occults TYC 5517-00227-1 on 2018 Feb 22 from 11h 19m to 11h 31m UT
Star:                              Max Duration =  5.0 secs          Asteroid:
Mv = 10.2                            Mag Drop =   5.7                  Mag =15.9
RA = 11 46 47.6027 (J2000)         Sun :   Dist = 152 deg             Dia  =  59km,   0.032"
Dec = - 8 27 14.404                Moon:   Dist =126 deg              Parallax = 3.470"
[of Date: 11 47 44, - 8 33 19]          :   illum = 40 %              Hourly dRA =-1.383s
  Prediction of 2018 Jan 17.0      E 0.027"x 0.013" in PA 78          dDec = 10.80"
```

http://www.asteroidoccultation.com/

the 59km diameter asteroid will occult a 10.2^m star, mag. will drop by 5.71^m for at most 5.0s 50% chance the shadow would cross over FLWO.
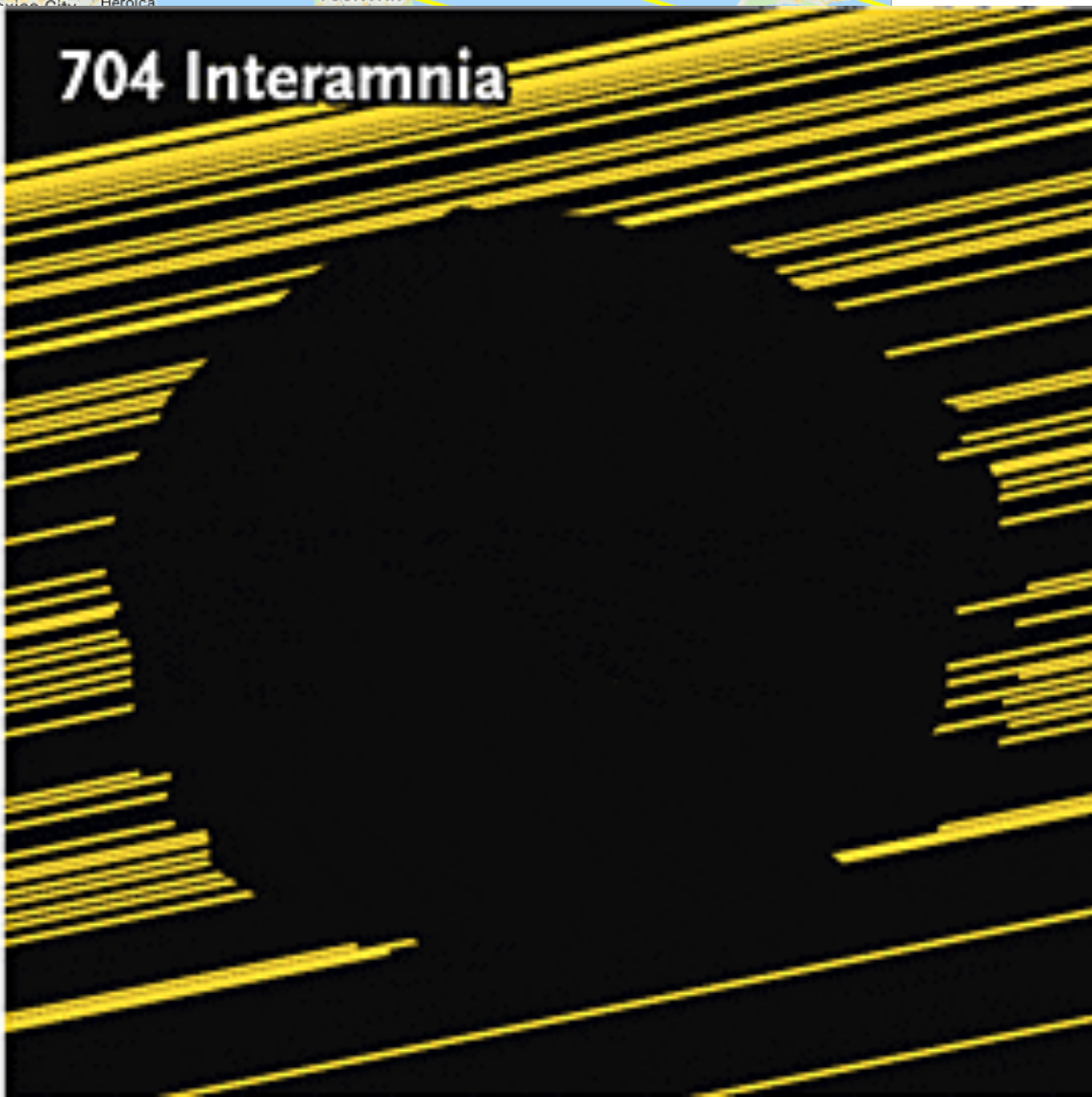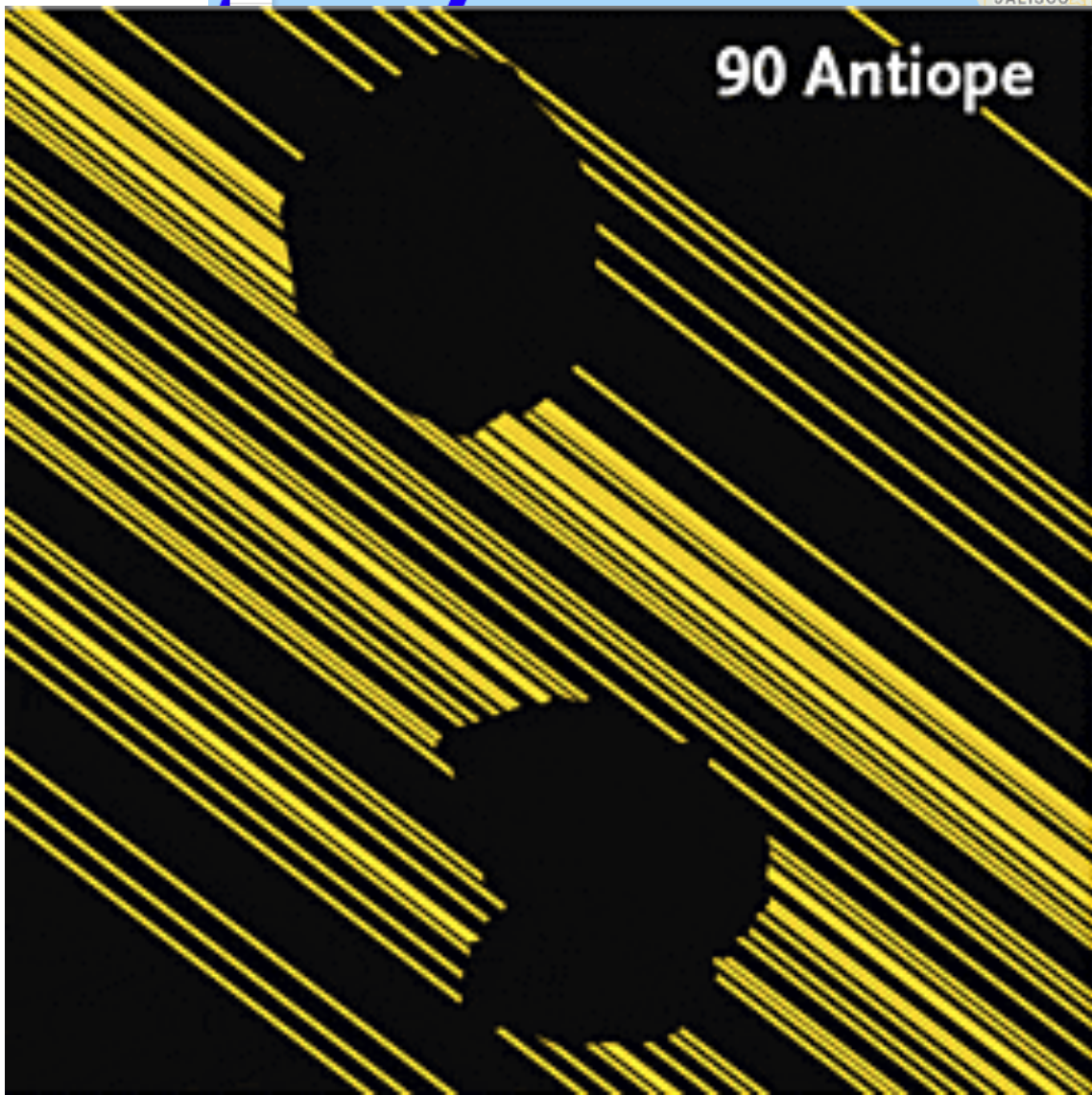
The nice thing is that even a non-detection of the shadow tells something about the size/shape of the asteroid
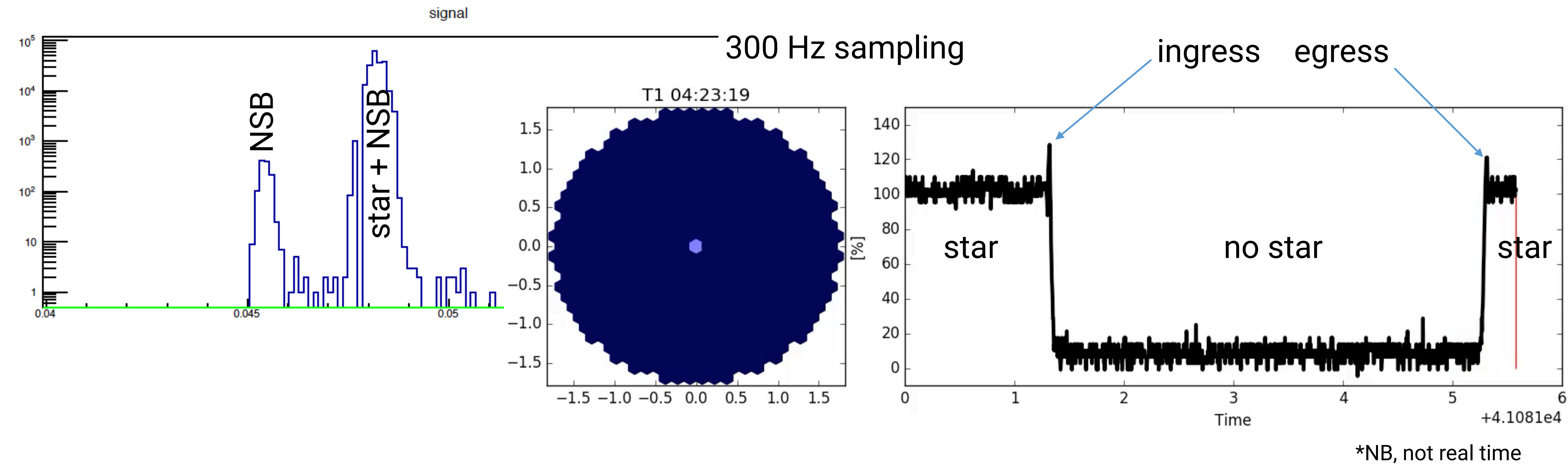
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To resolve a star so faint required an upgrade to the pixel current monitor

(1165) Imprinetta / TYC 5517-227-1 occultation

signal

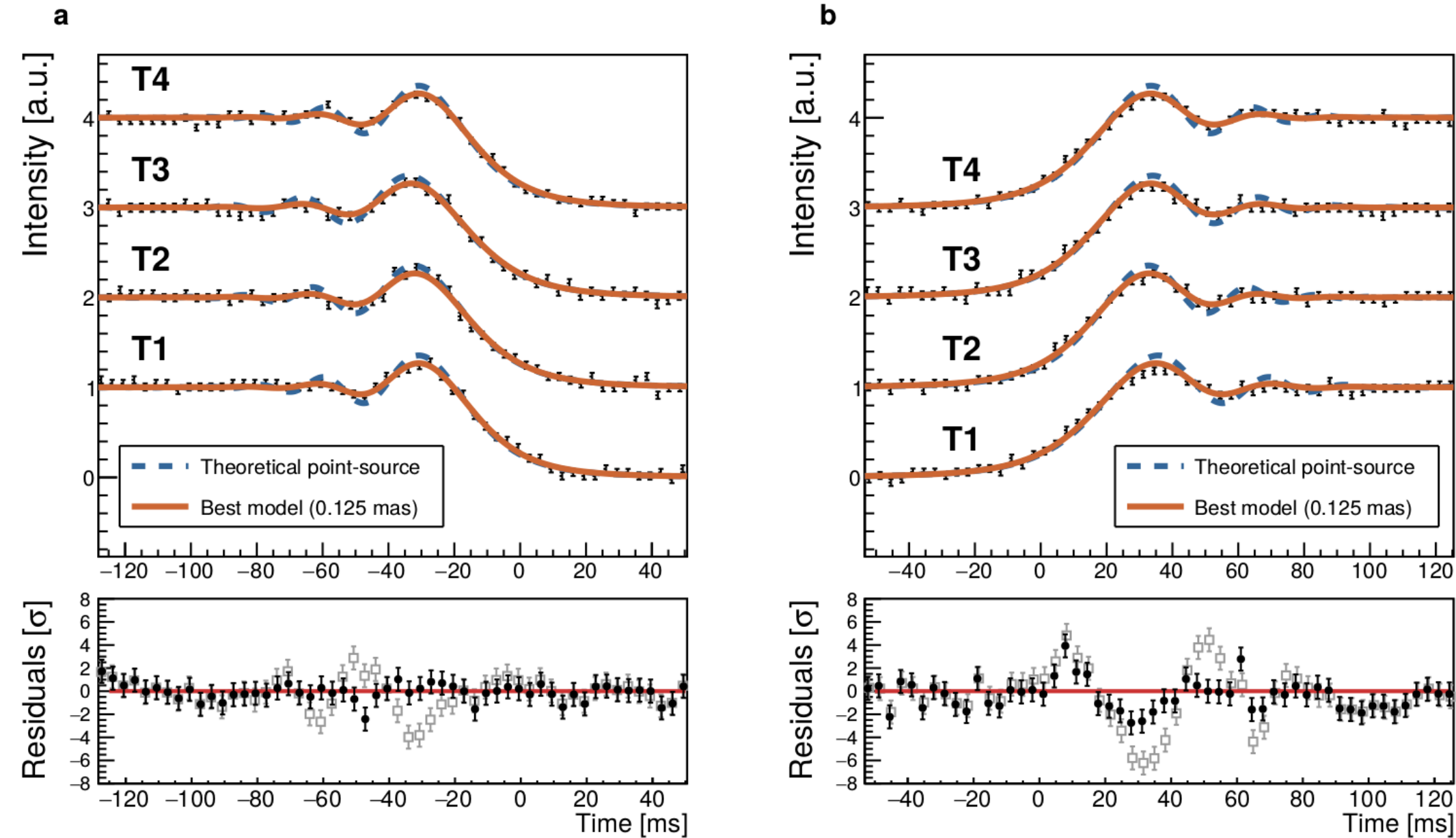**300 Hz sampling**
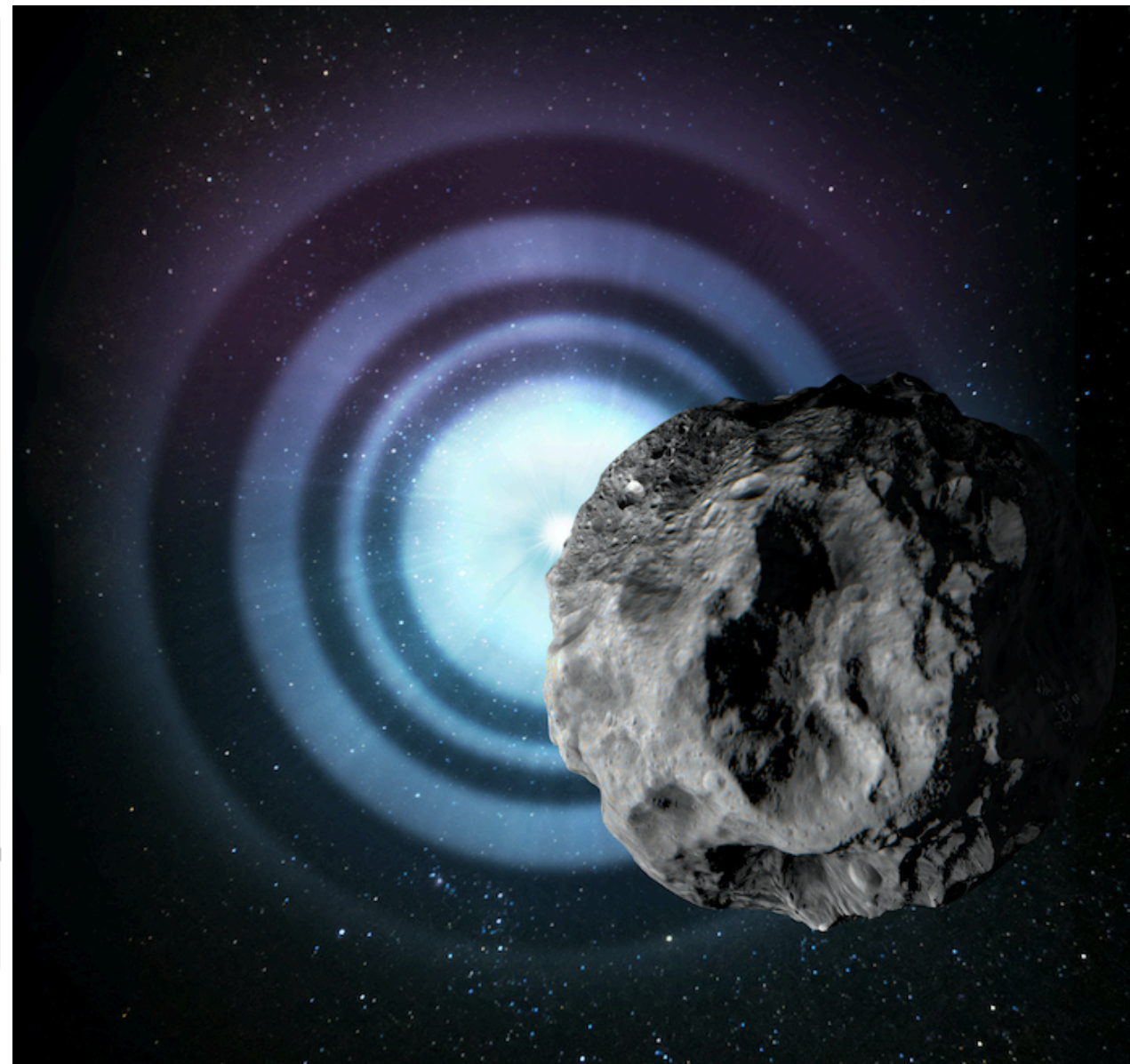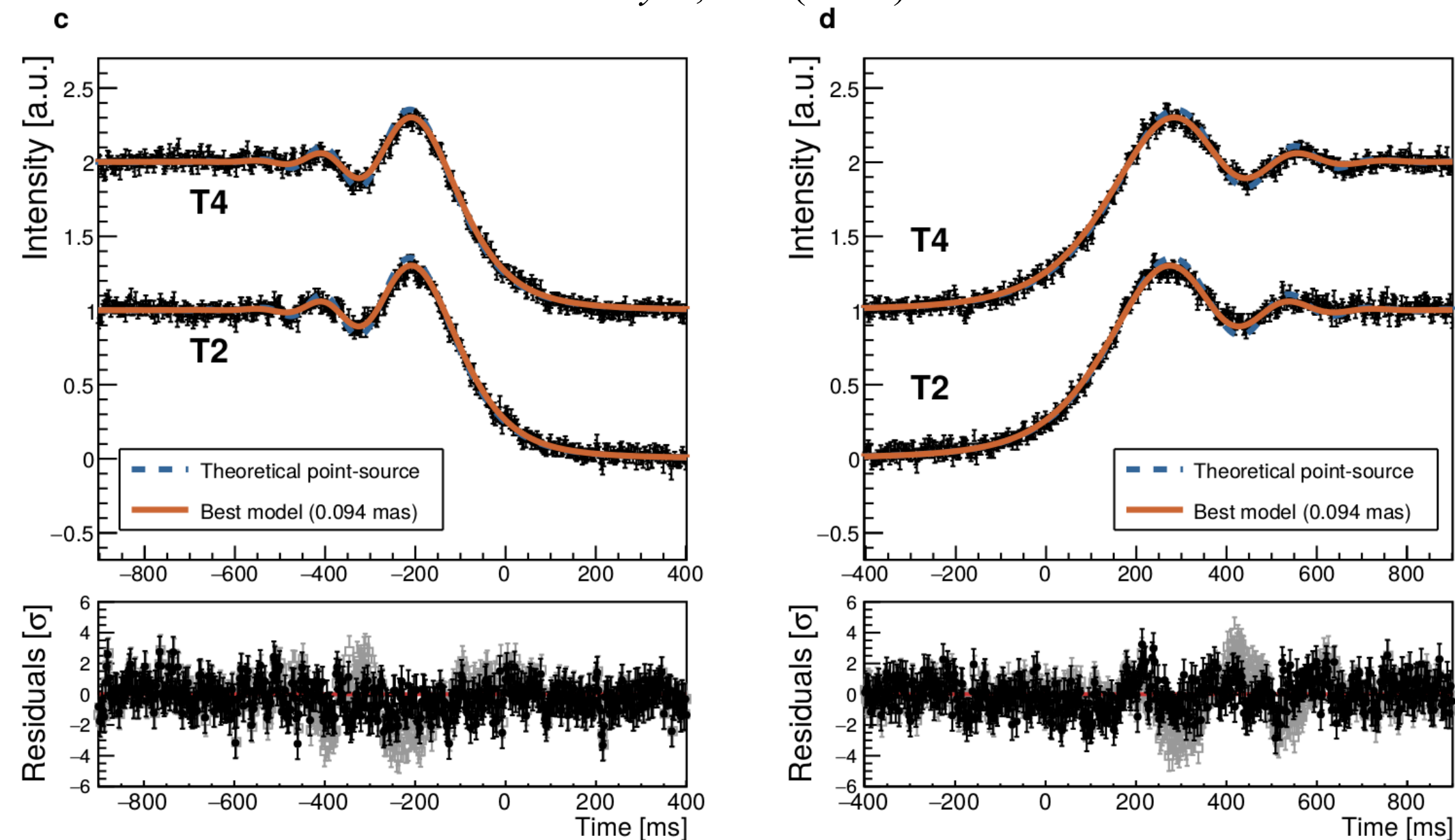
NSB

star + NSB

T1 04:23:19

ingress   egress

star

no star

star

*NB, not real time

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Wave

Particle

IACT – the detector

IACT – the science?

IACT – the science

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HARVARD & SMITHSONIAN
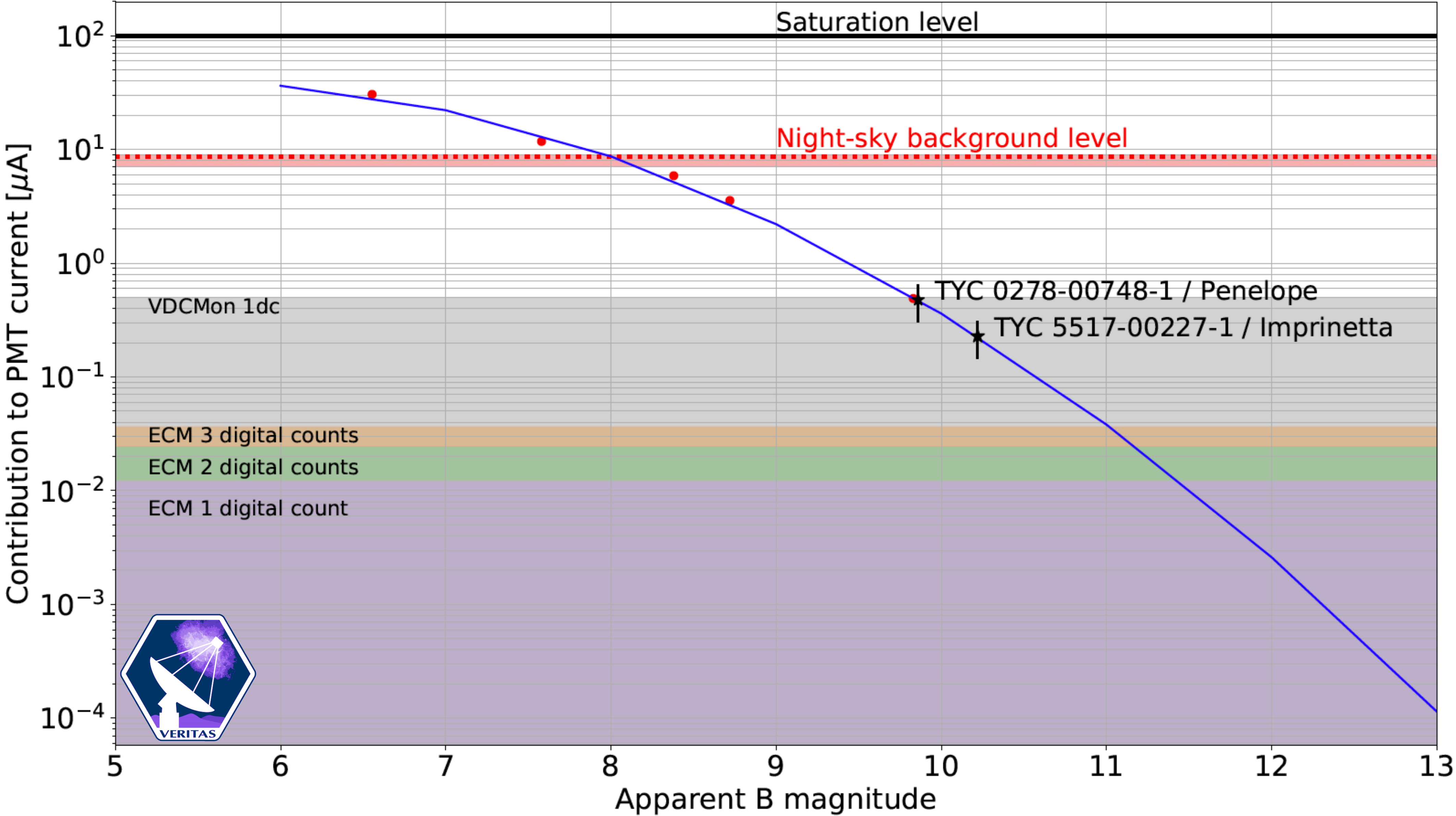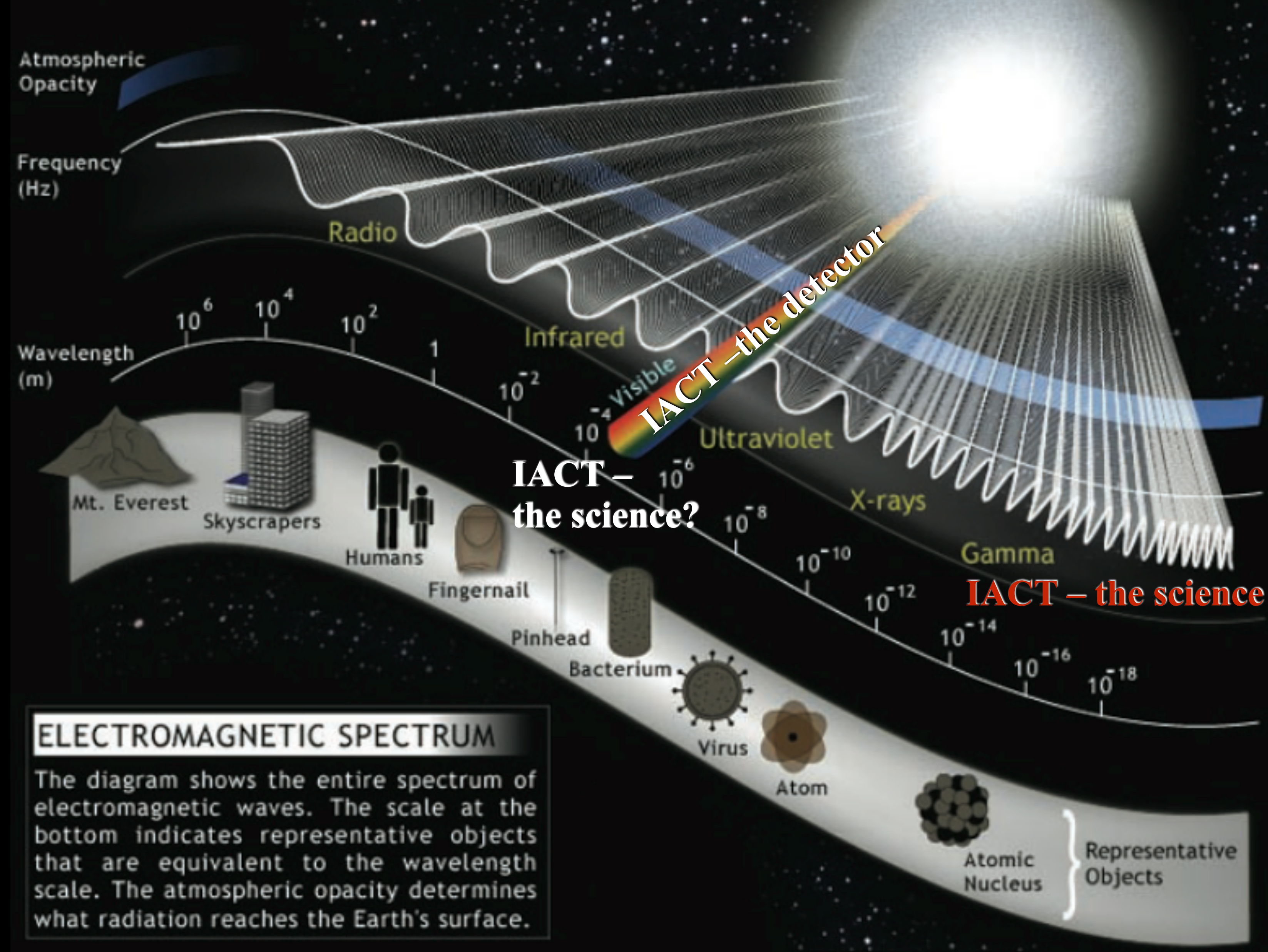
The fringe benefits of asteroid occultations

Telescope PSF → point-like source
But, not actually a point source:
from the diffraction pattern in the shadow
we get the angular size of the star!

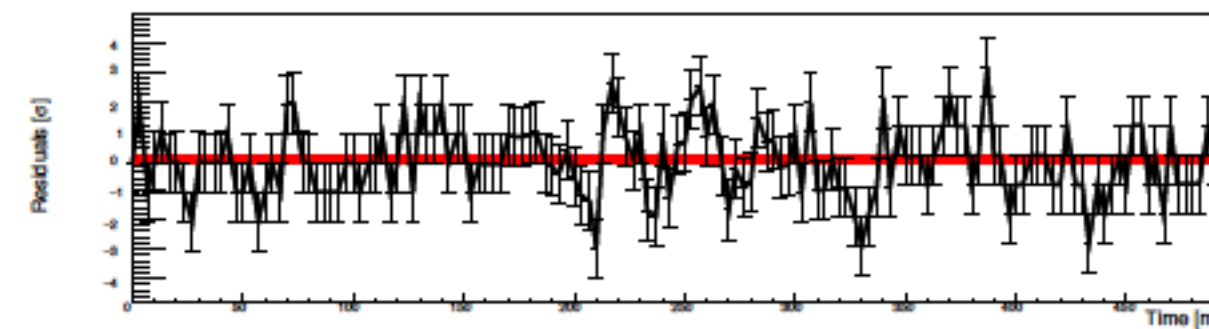Benbow et al. *Nature Astronomy* **3**, 511 (2019).
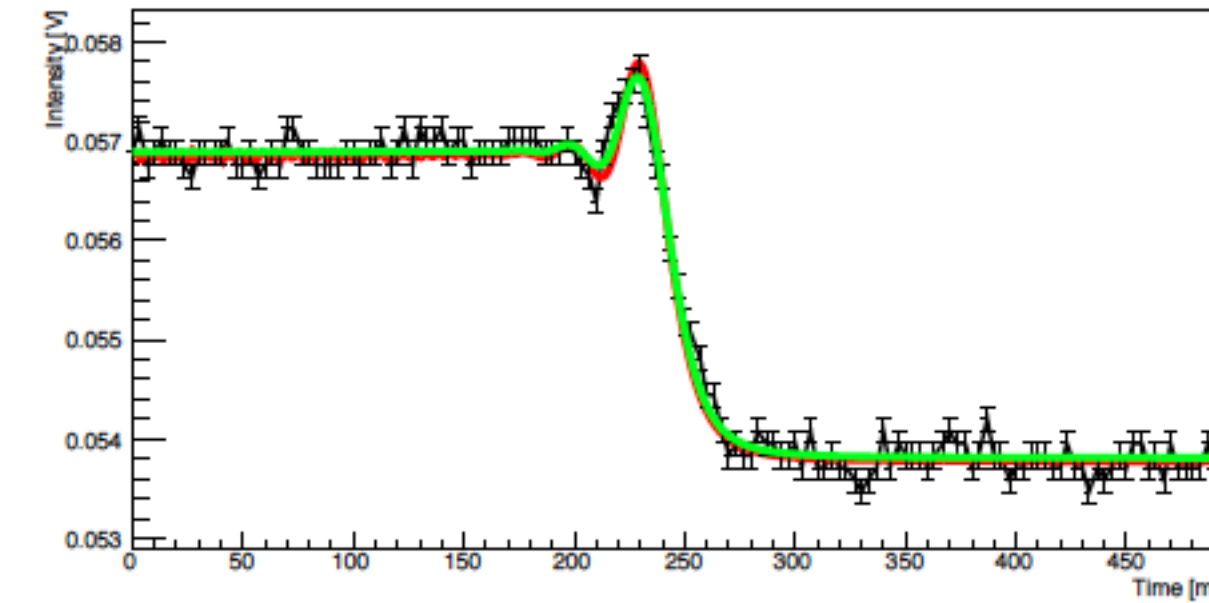
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The extent of the light source reduces the fringe

Effect of a uniform circular disk on fringe pattern

point source
disk diam 5 mas
disk diam 10 mas
disk diam 15 mas
disk diam 20 mas
disk diam 30 mas
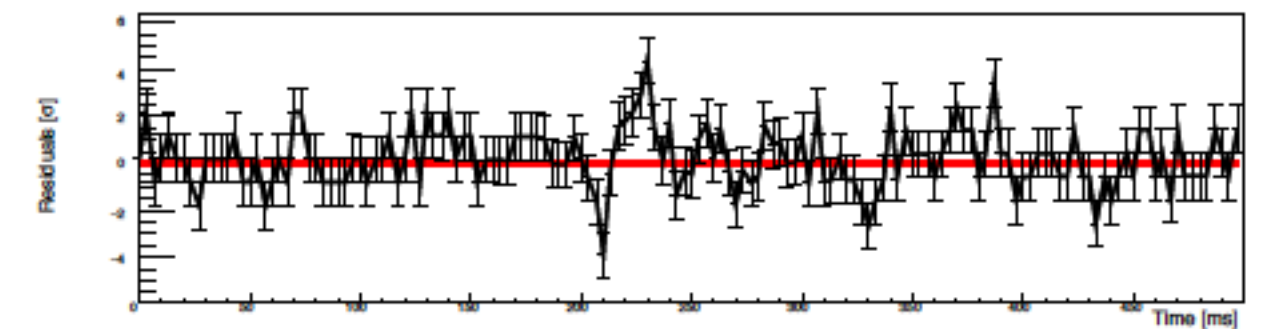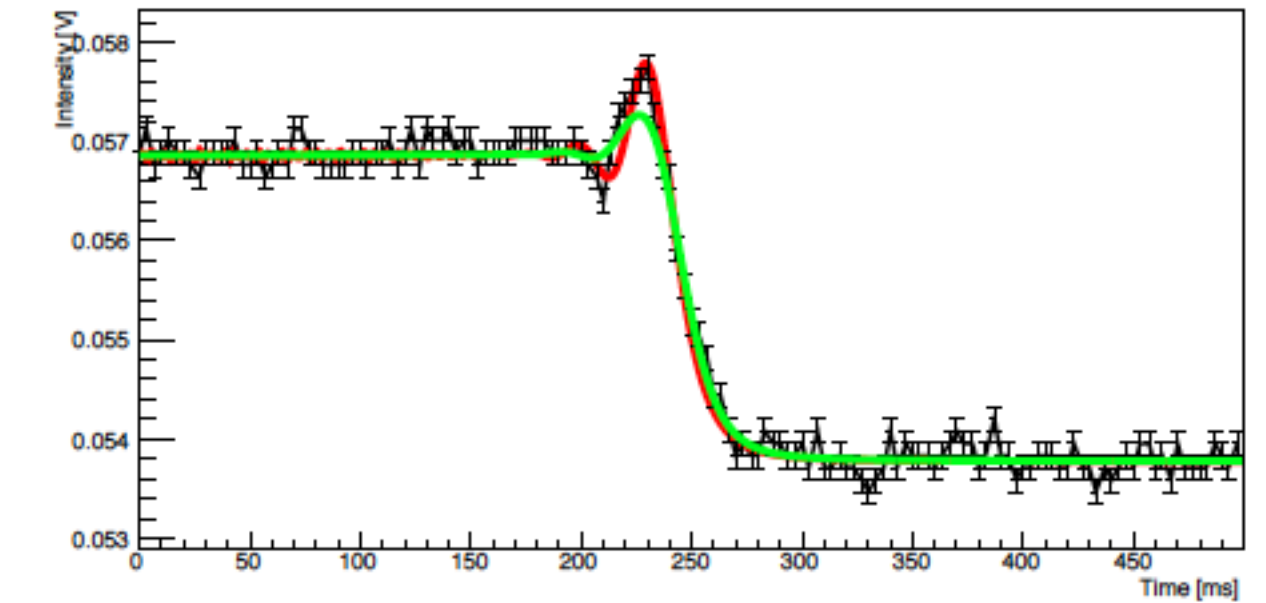disk diam 45 mas

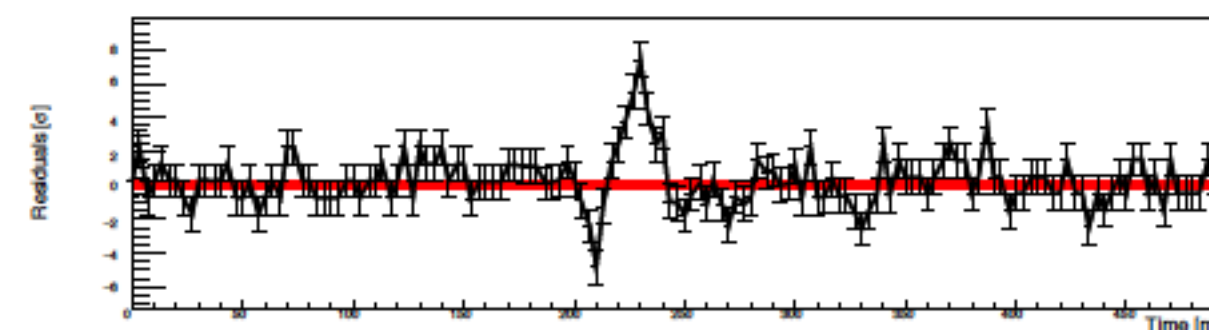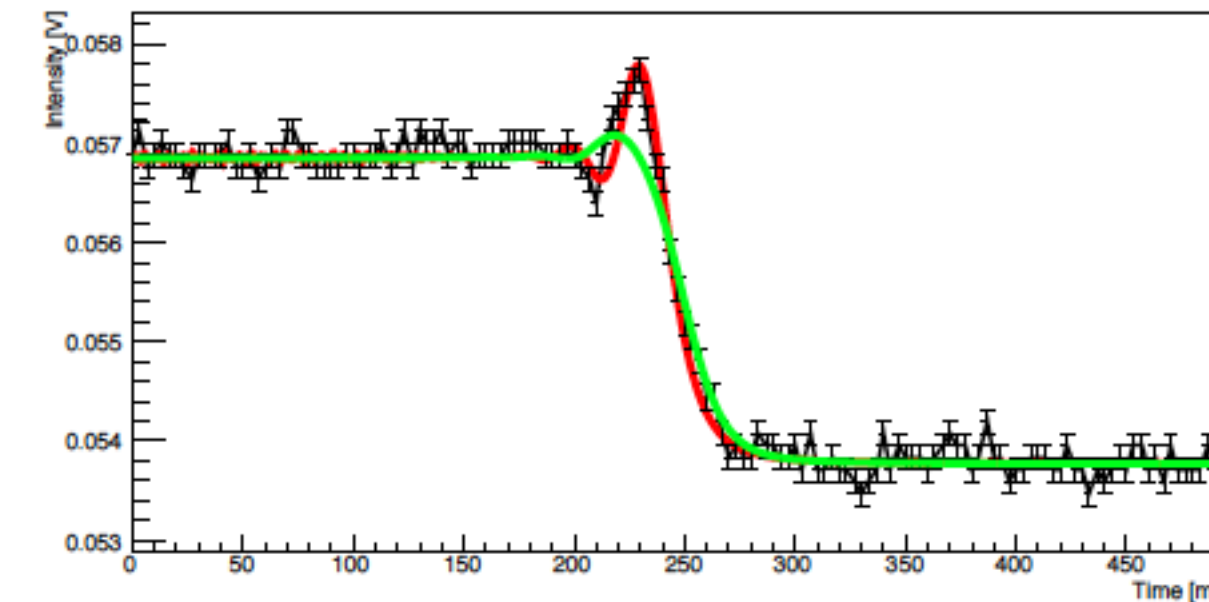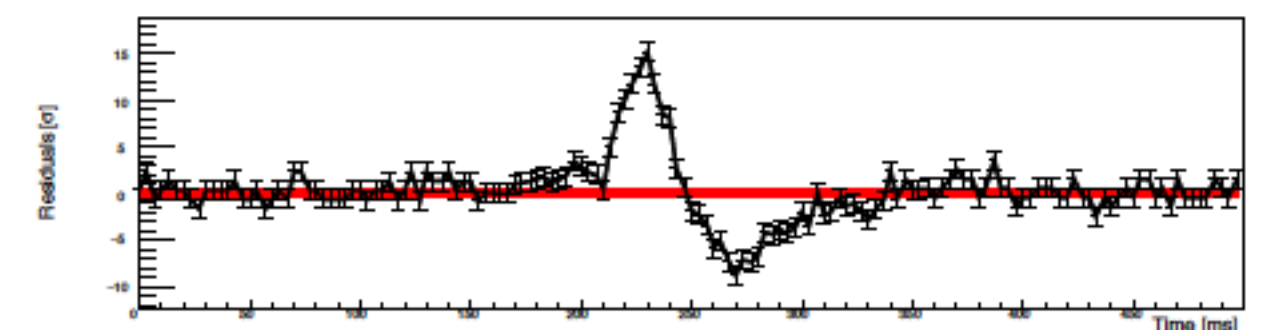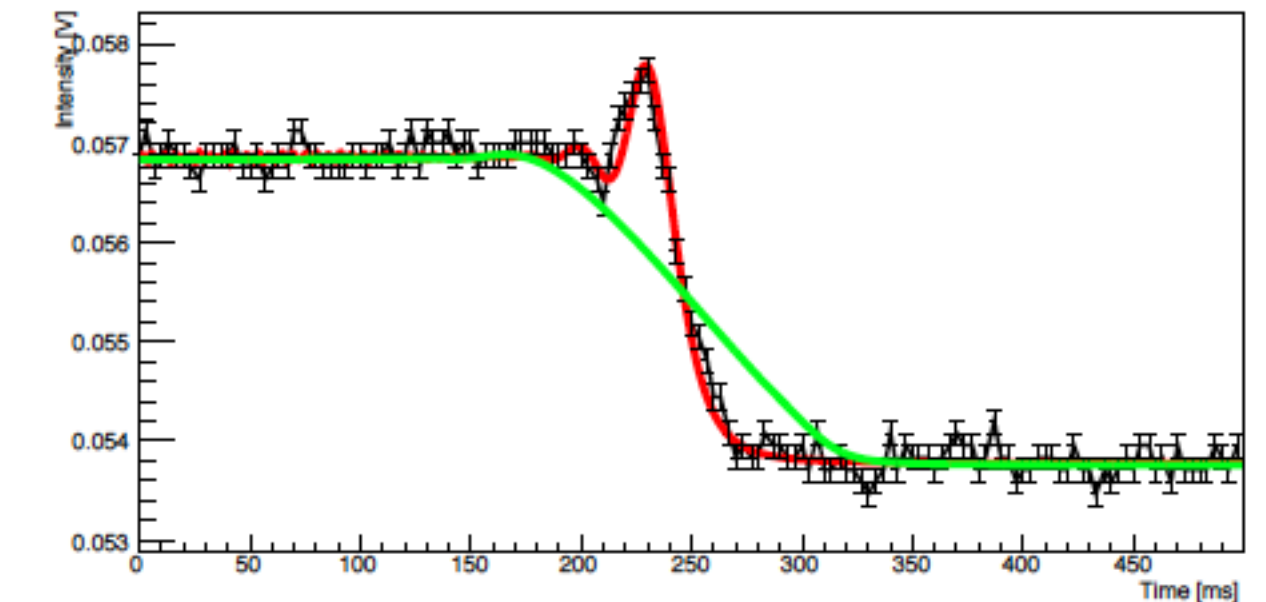http://spiff.rit.edu/richmond/occult/bessel/bessel.html
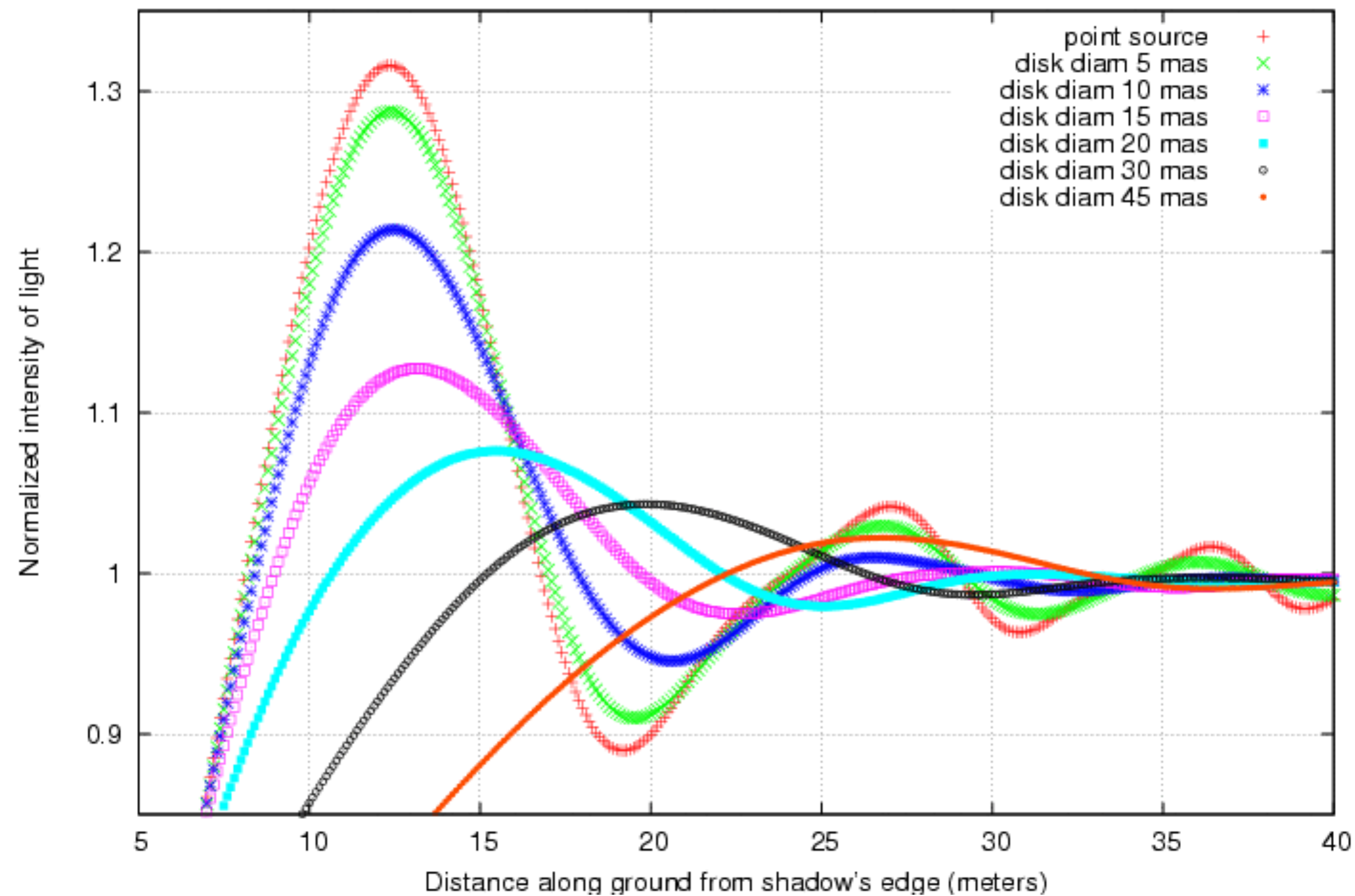
Central pixel of T1, star size of 0.10 mas
Central pixel of T1, star size of 0.20 mas
Central pixel of T1, star size of 0.30 mas
Central pixel of T1, star size of 1.00 mas

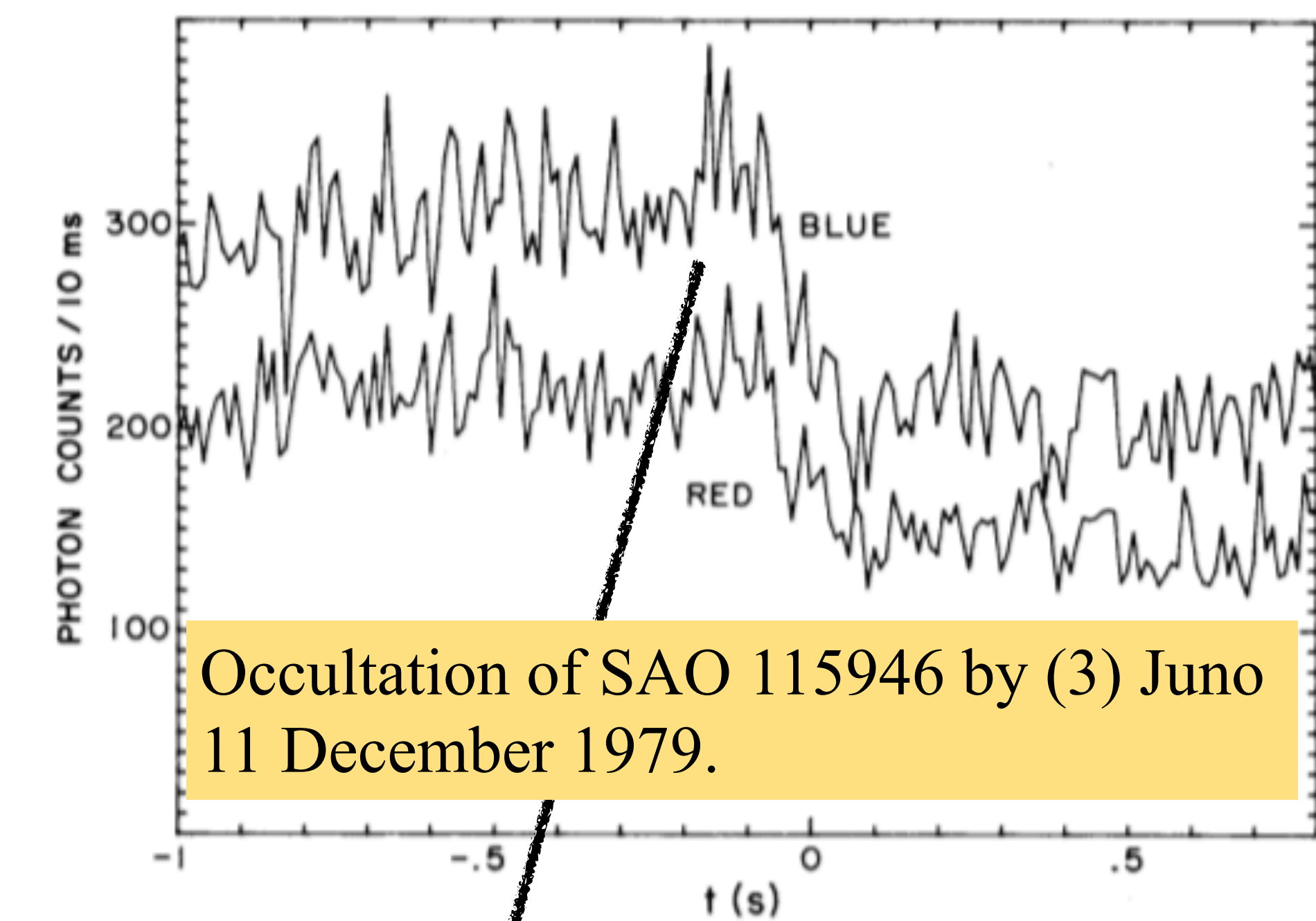CENTER FOR ASTROPHYSICS
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FIG. 2. Ludlow immersion. Each 10-ms data point in the red and blue channels is shown. Note the correlation between red and blue signals (especially at 0°.45) caused by scintillation.

Occultation of SAO 115946 by (3) Juno 11 December 1979.

RED COMPOSITE

>50% uncertainty

2x 36cm Celestrons

Reitsema et al. *AJ* **86**, 121 (1981)
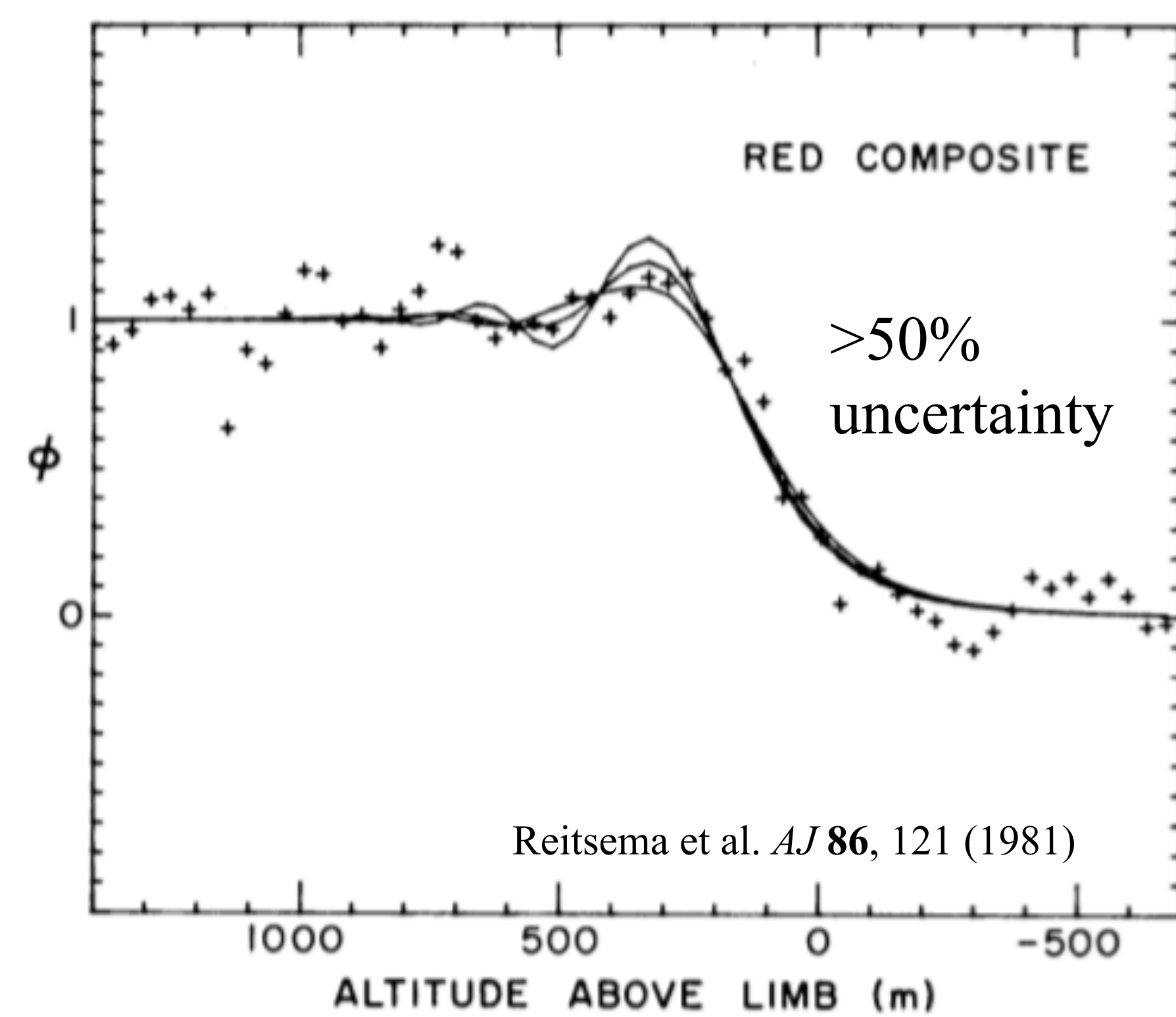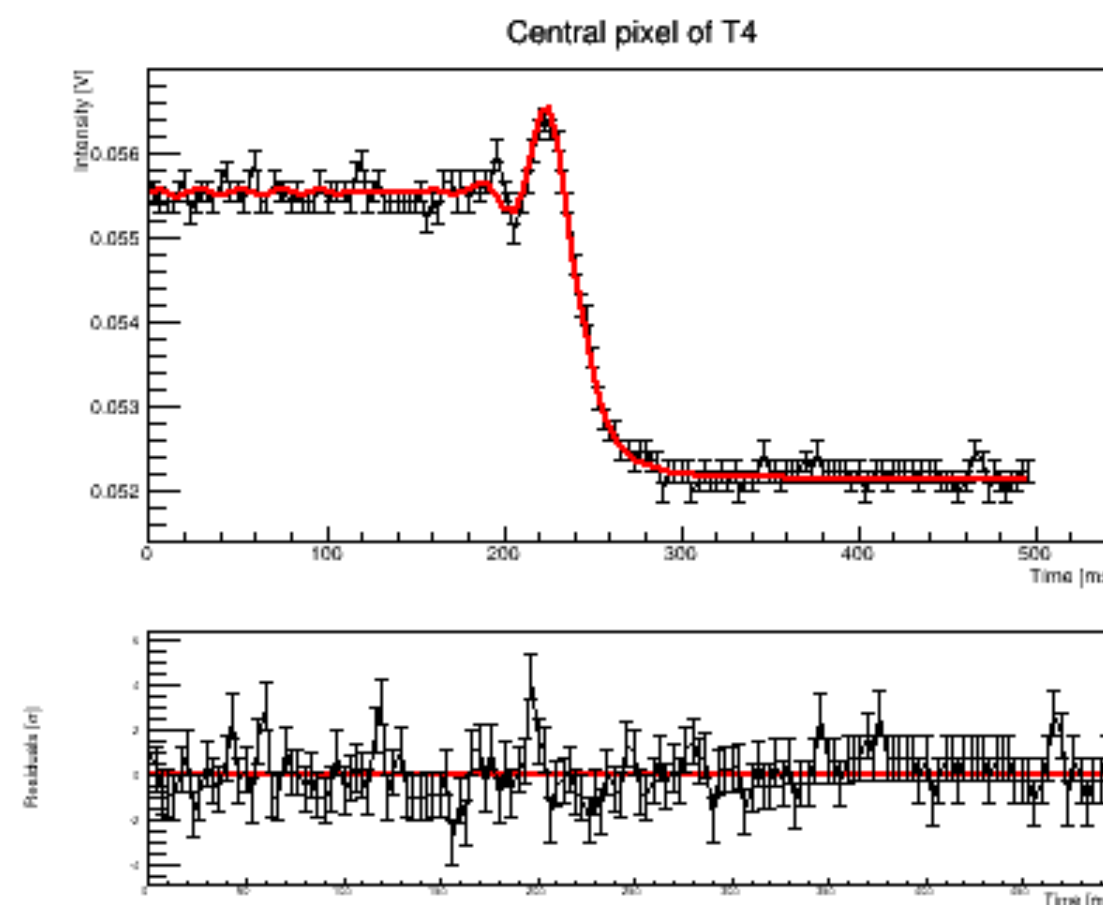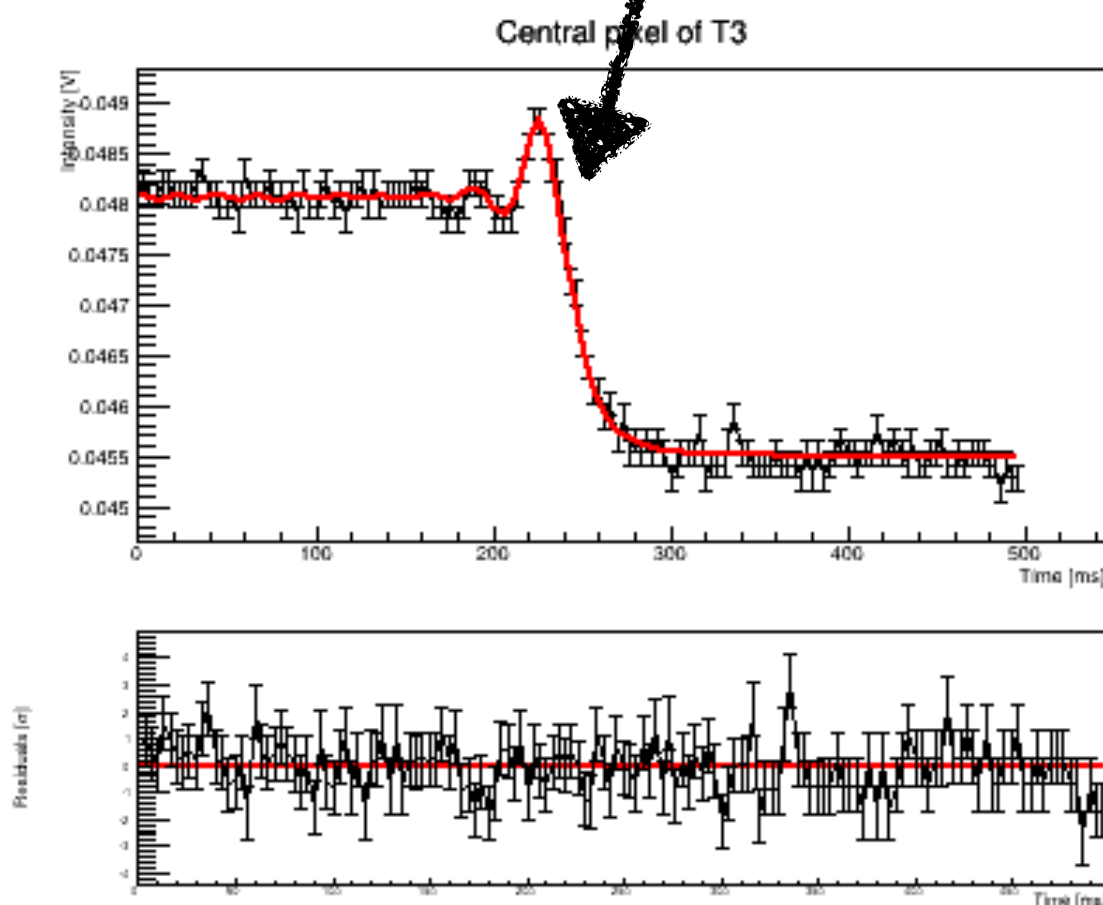
FIG. 4. Same as Fig. 3, but for the red averages.

4x 12m "light buckets"

Occultation of TYC 5517-227-1 by (1165) Imprinetta 22 February 2018.

Benbow et al. *Nature Astronomy* **3**, 511 (2019)

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An IACT is optimal for a population of small/faint stars
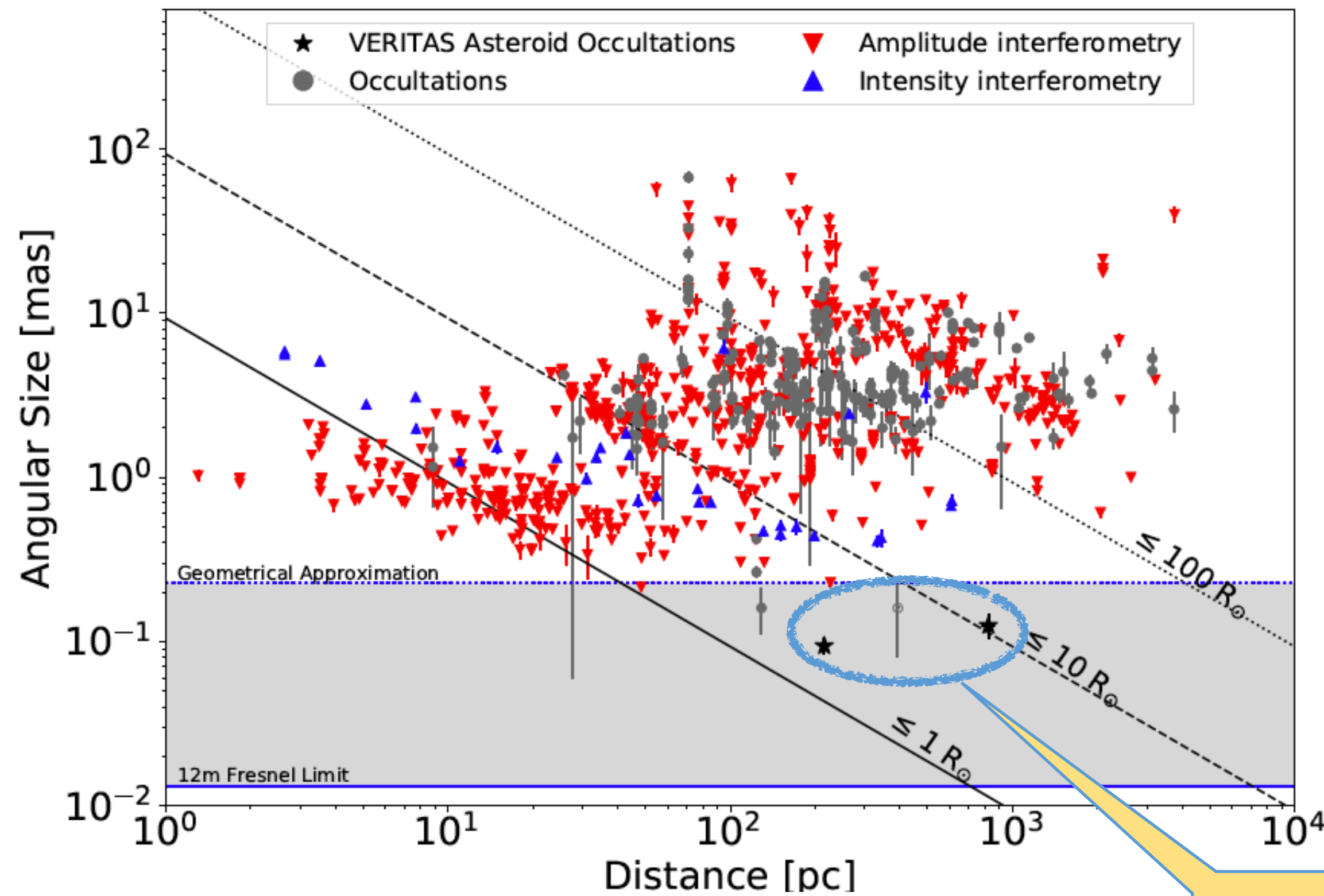
See poster PS1-66 (session 1)

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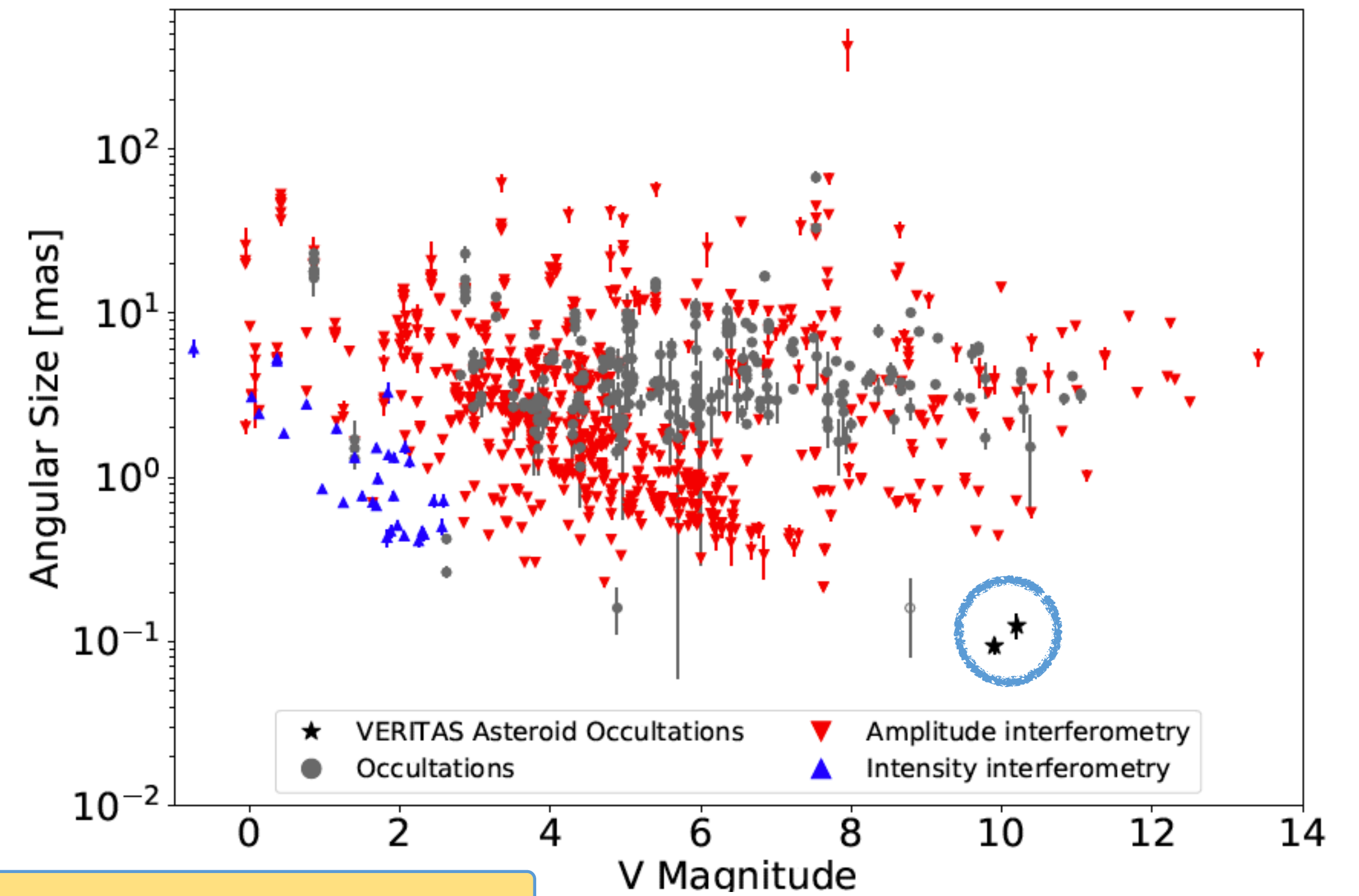# Why are we interested in the radius of small, faint stars?

$$\text{Transit Depth} = \left(\frac{R_p}{R_*} \right)^2$$

Image:M. Weiss/CfA

G Dwarf
1 x Solar Radii

M Dwarf
0.5 x Solar Radii

Brightness

Time

Brightness

Time

https://www.cfa.harvard.edu/~avanderb/tutorial/tutorial.html

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a — TYC 5517-00227-1

820 ± 40 pc
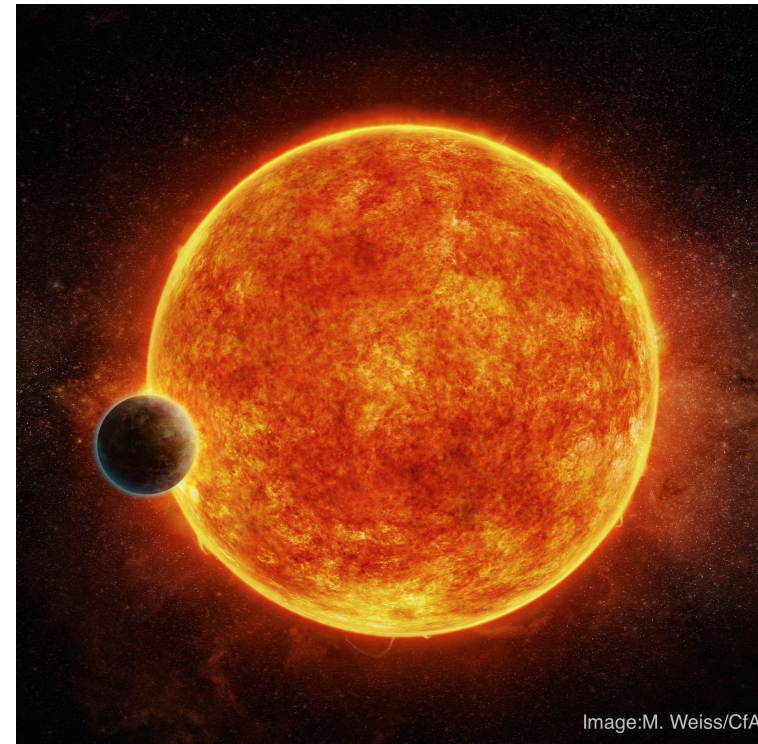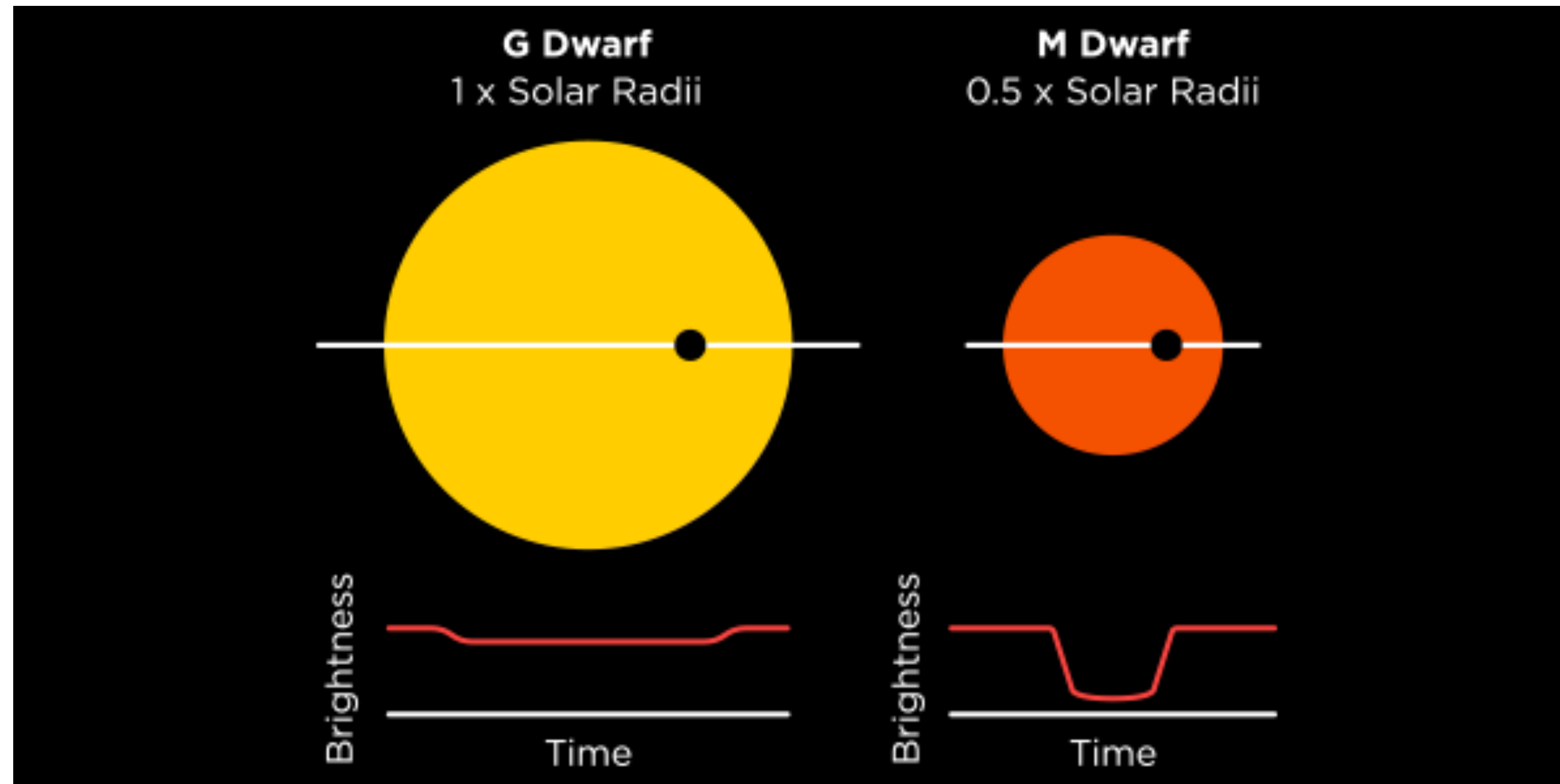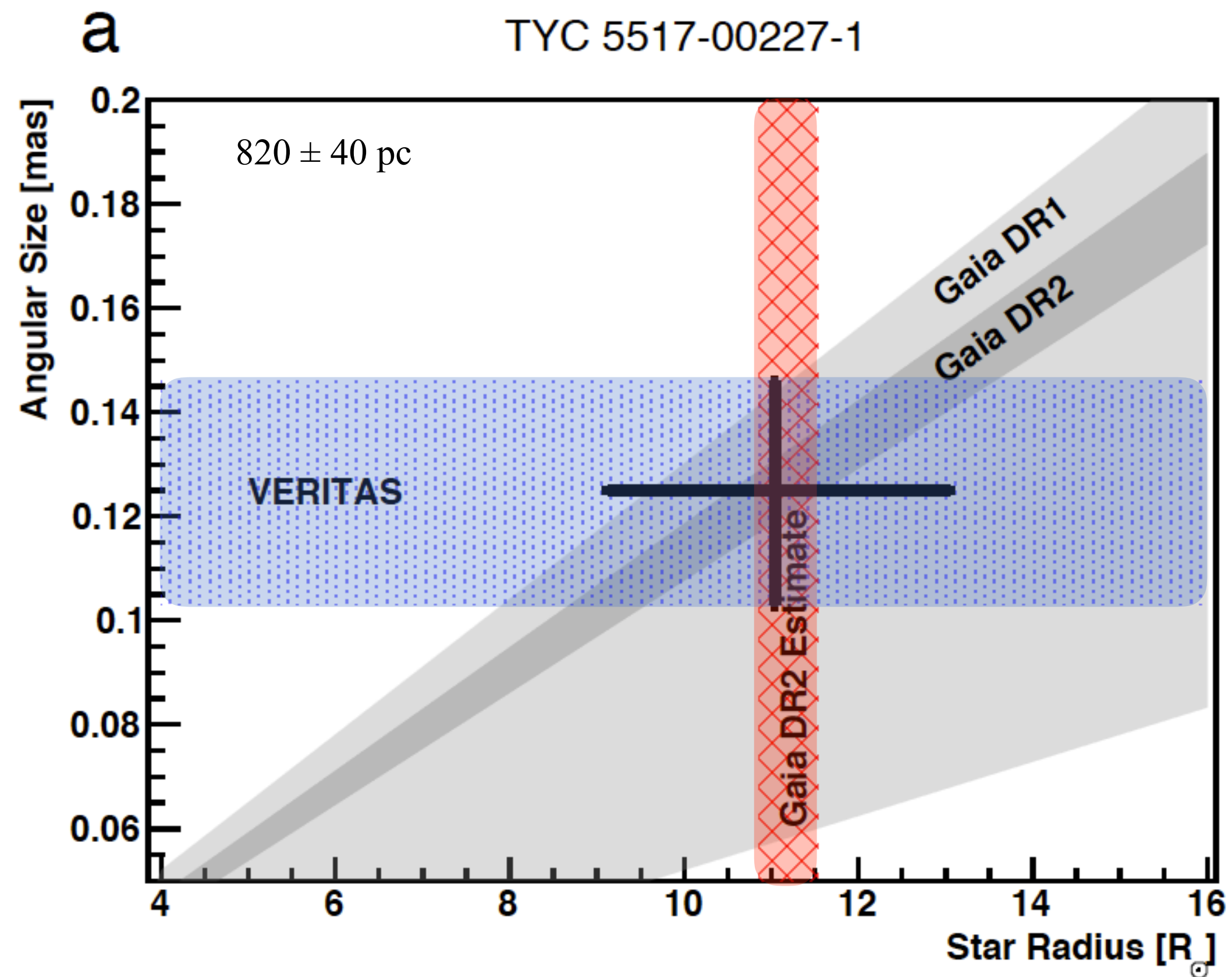
Direct measurement resolves star to be supergiant (KIII)

b — TYC 0278-00748-1

215 ± 2 pc
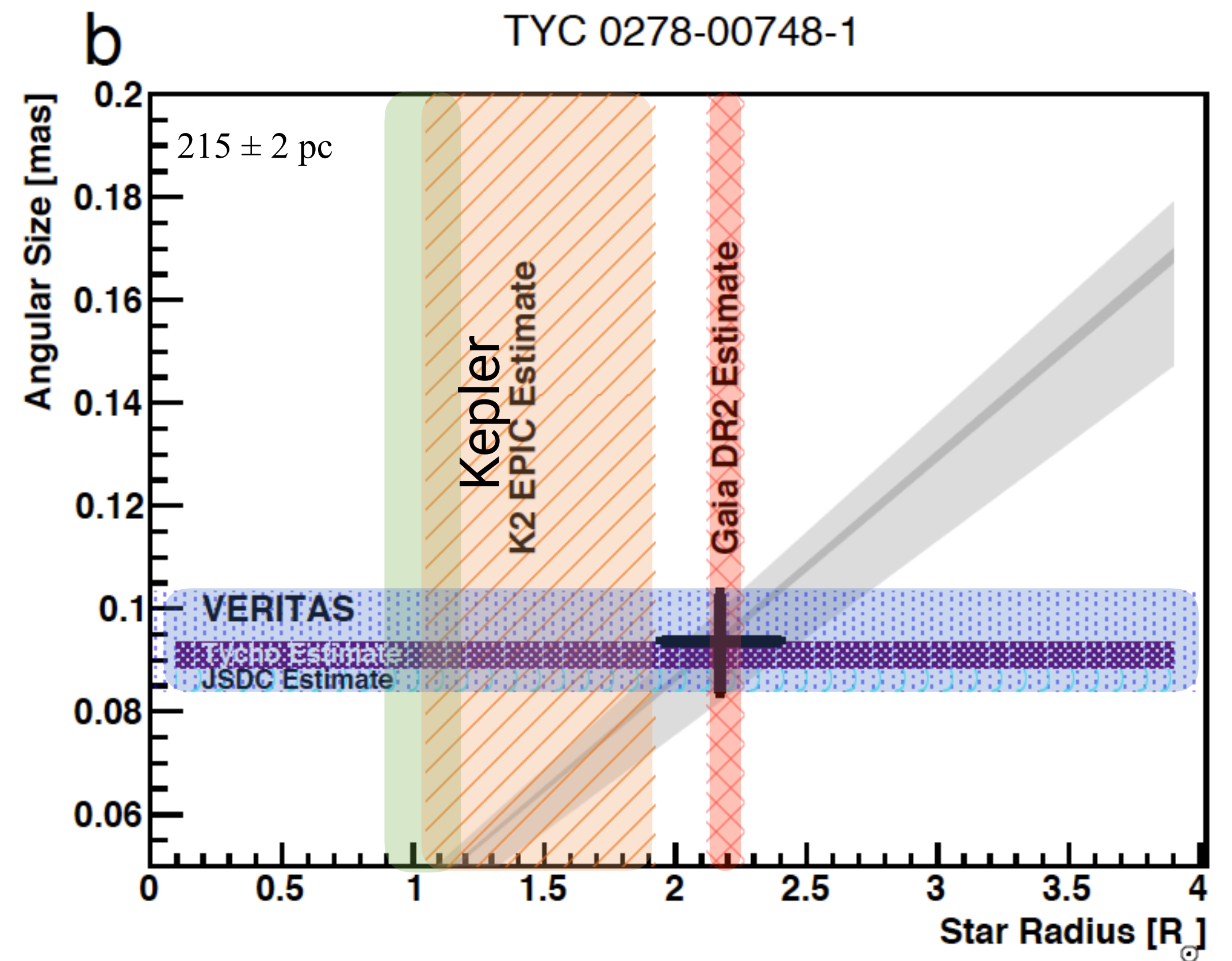
Direct measurement resolves star to be sub-giant (GIV) and not main sequence (GV)
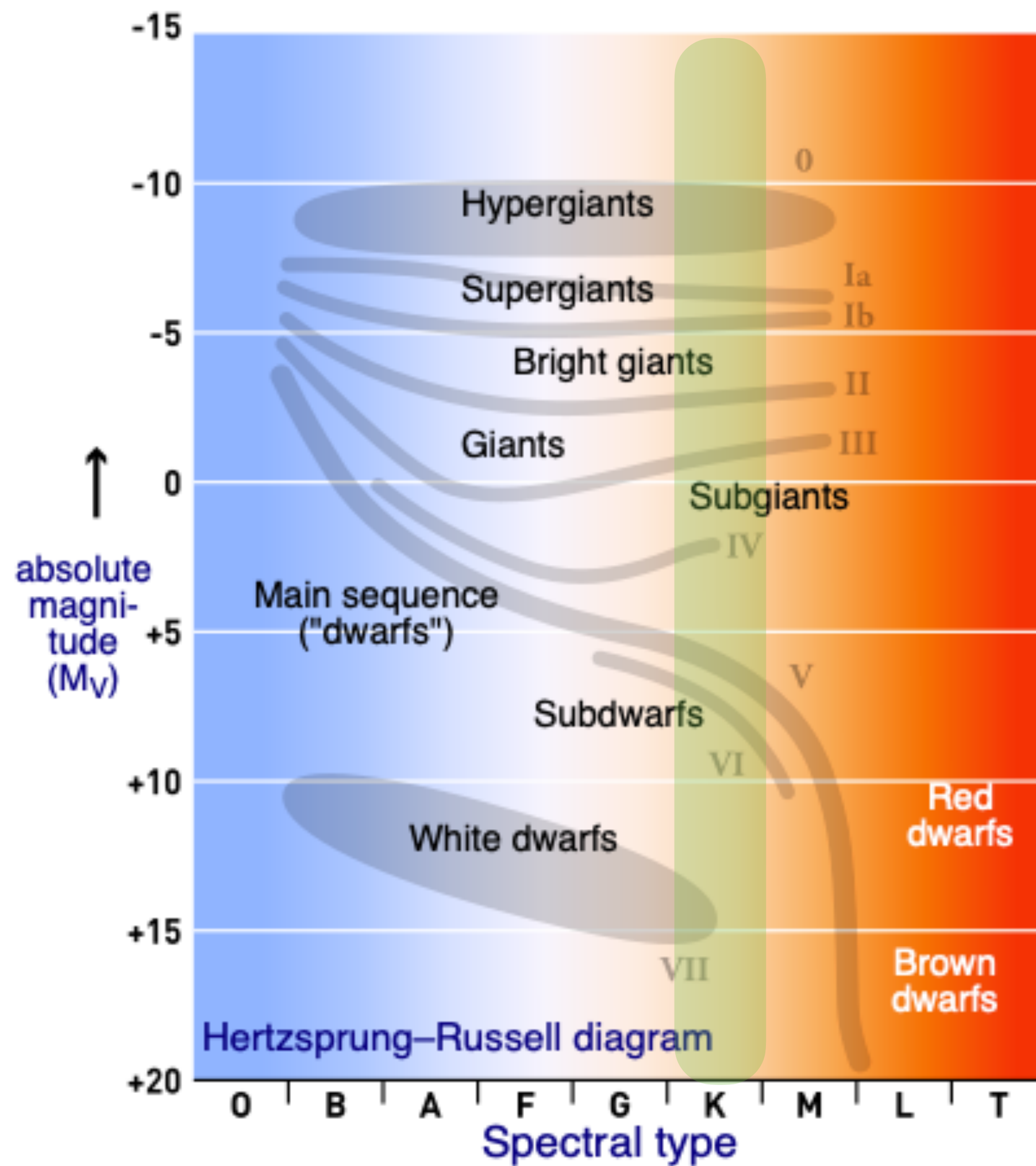
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Why are we interested in small, faint stars?

There's a particular interest in K star radii, since there is growing evidence of a discrepancy between models and reality at the ~5% level

Spada et al. *ApJ* **776**, 87 (2013)

$$\langle\delta R/R\rangle(\text{all}) = 0.0310$$
$$\langle\delta R/R\rangle(P_{orb} < 1.5\ d) = 0.0532$$
$$\langle\delta R/R\rangle(P_{orb} > 1.5\ d) = 0.0132$$
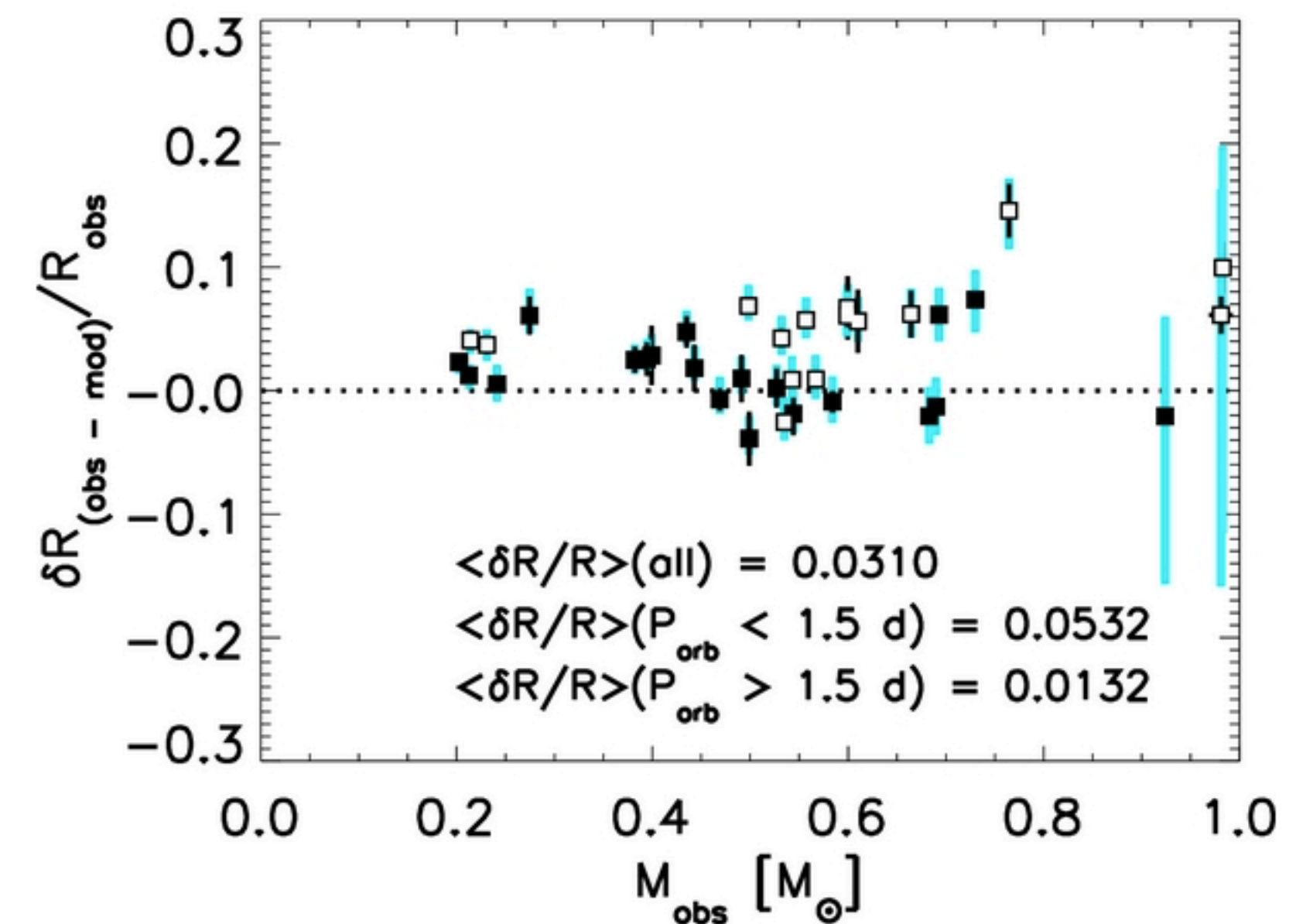
Why are we interested in small, faint stars?

$$\text{Transit Depth} = \left(\frac{R_p}{R_*}\right)^2$$

There's a particular interest in K star radii, since there is growing evidence of a discrepancy between models and reality at the ~5% level

O	~0.00003%
B	0.13%
A	0.6%
F	3%
G	7.6%
K	12.1%
M	76.45%

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Intensity Interferometry

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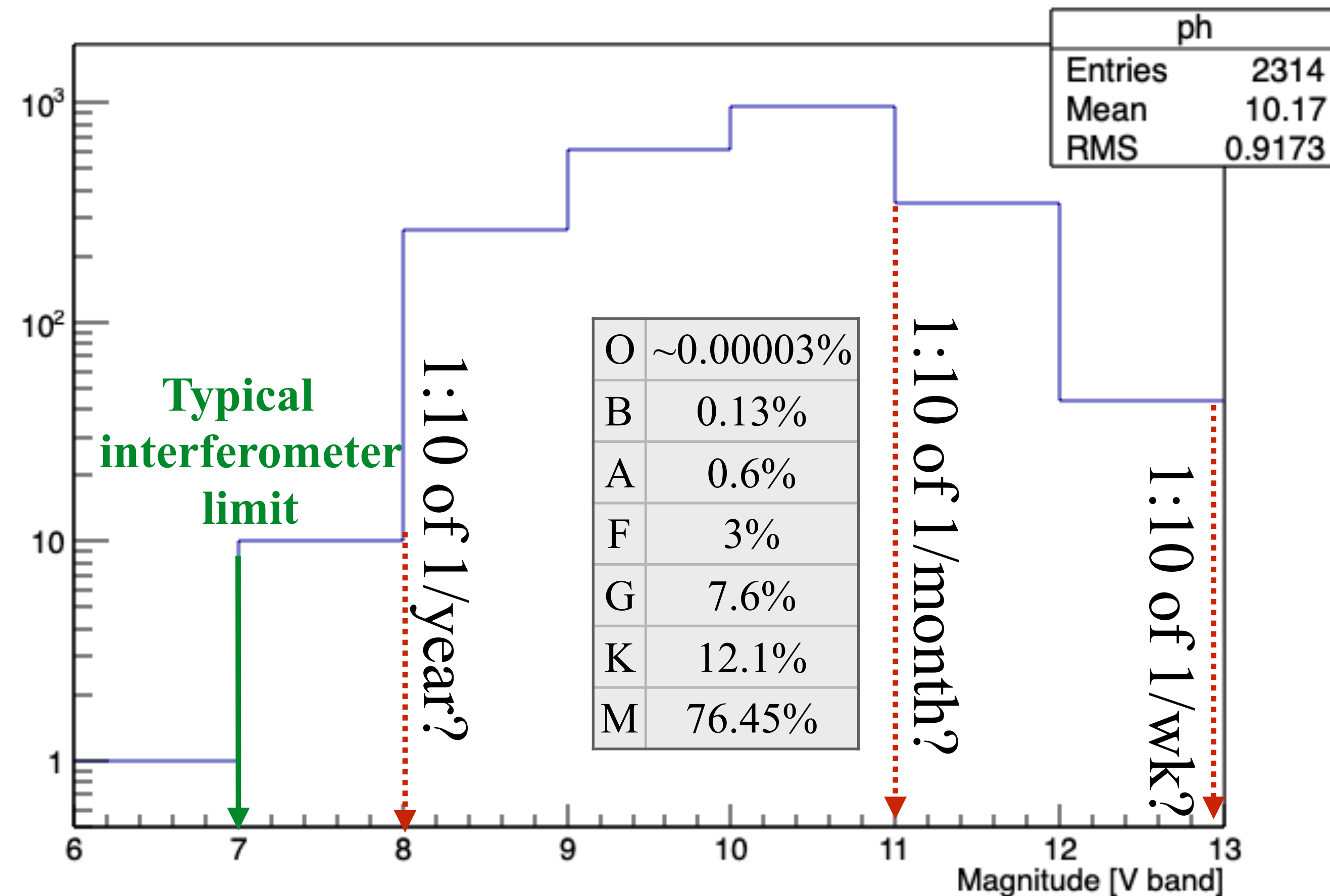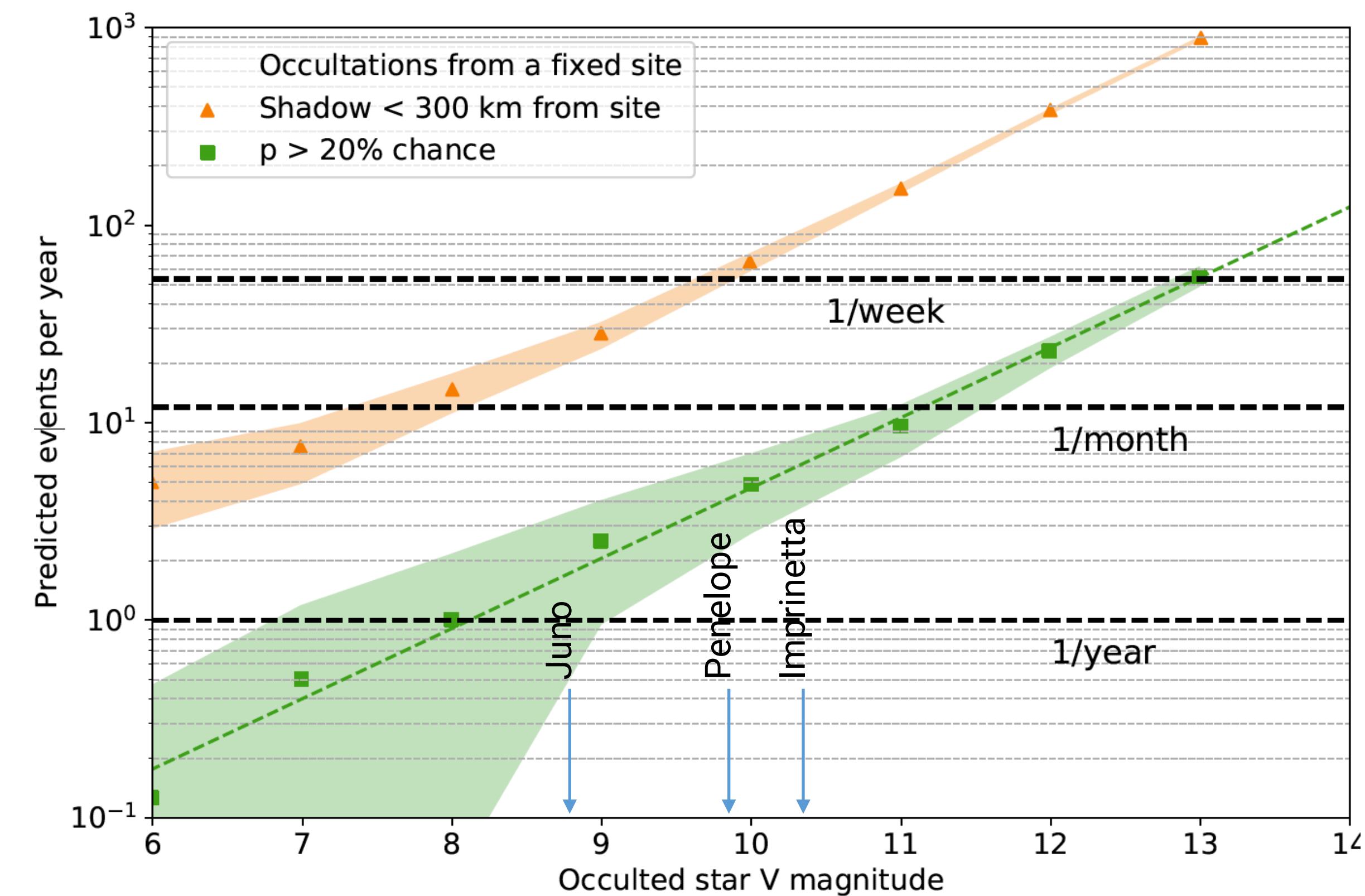
The motivation for sub-milliarcsecond astronomy
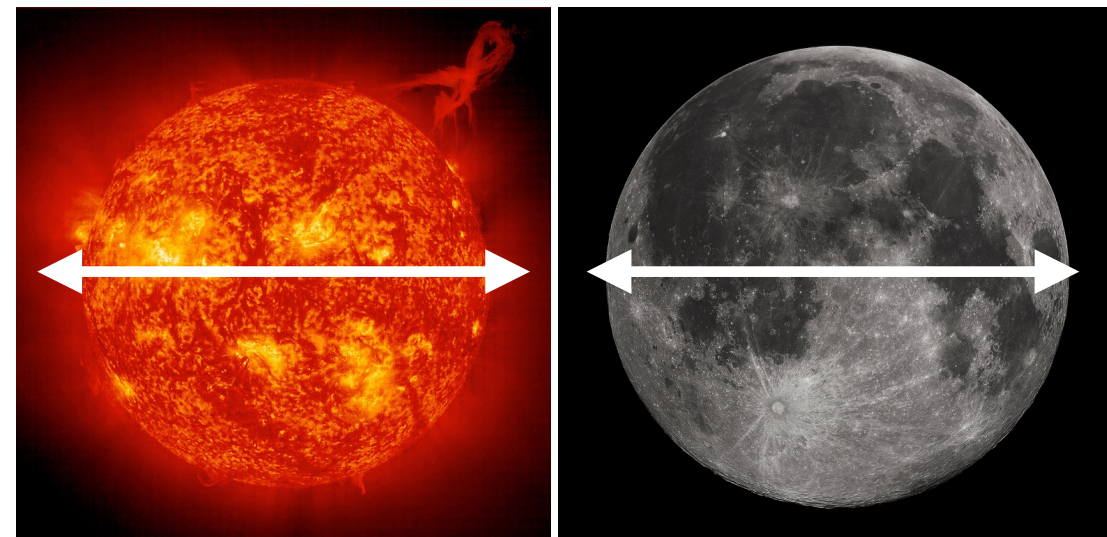
Sun, Moon
~30arcmin
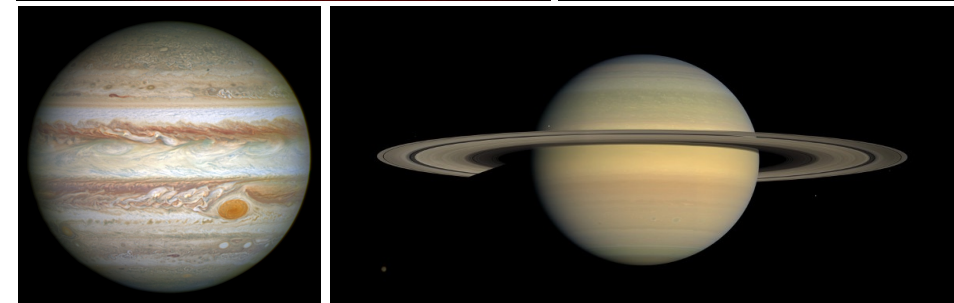
Local planets
~30arcsec

Largest stars
~30mas
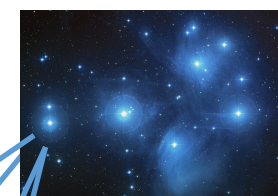
Typical bright stars
~1mas
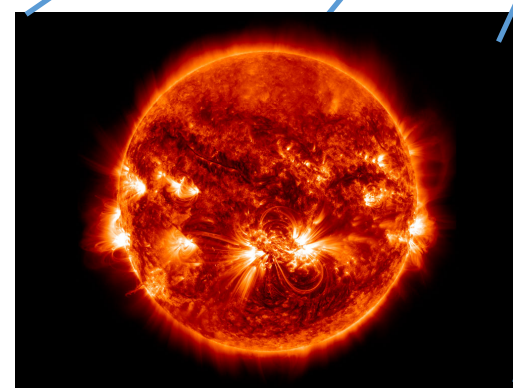
Many stars only become resolved
surfaces for baselines 100-1000m

$$\theta \sim \lambda/d$$

*Remember the interferometer is
"blind" to any scale that does not have
a baseline measurement*

d=1m @450nm

Angular size as a
function of distance

[mas]

10m

100m

1000m

		O	>6.6R$_\odot$
		B	>1.8R$_\odot$
		A	>1.4R$_\odot$
		F	>1.15R$_\odot$
		Solar Like	

Distance [pc]

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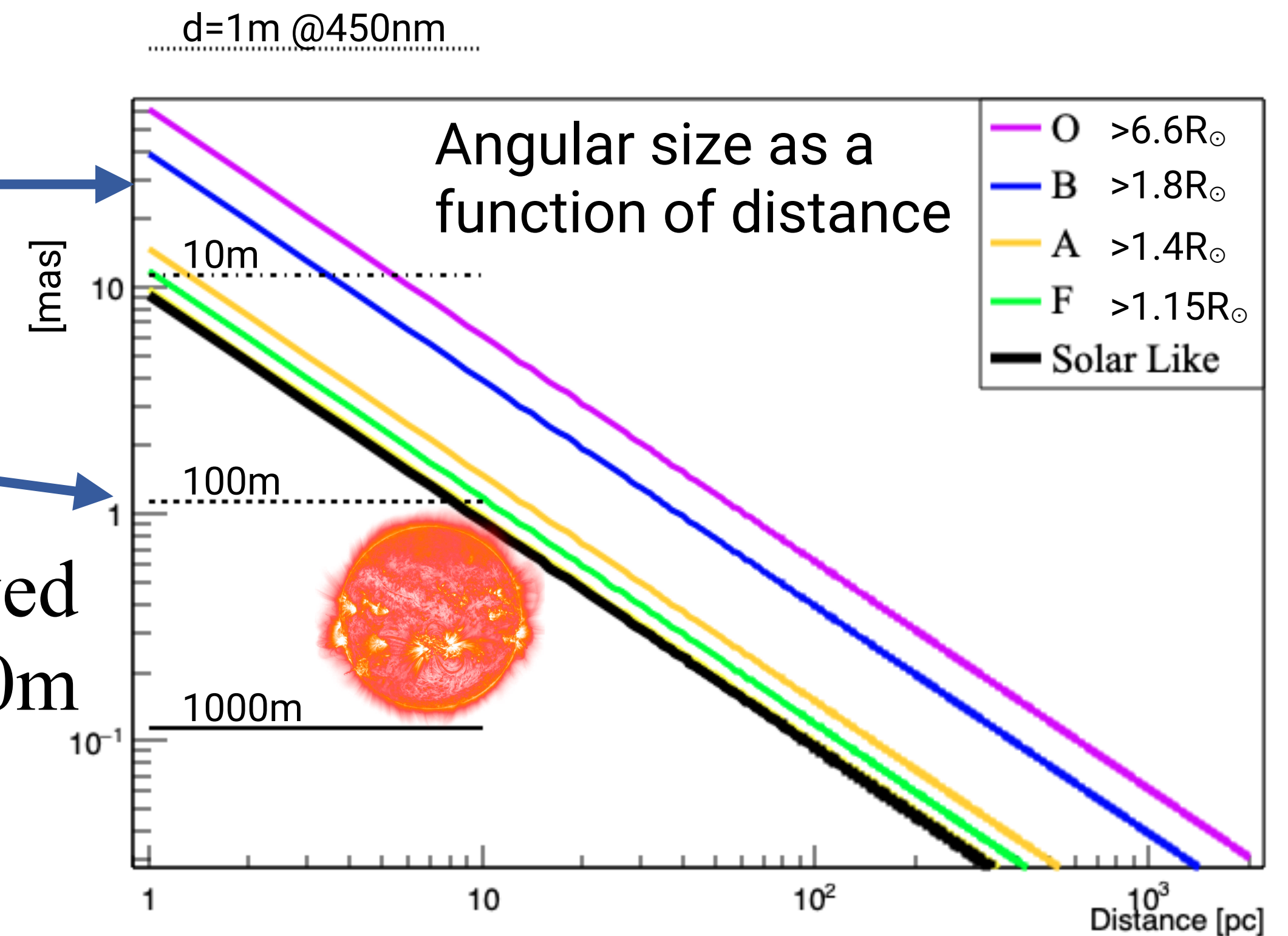
A little theory
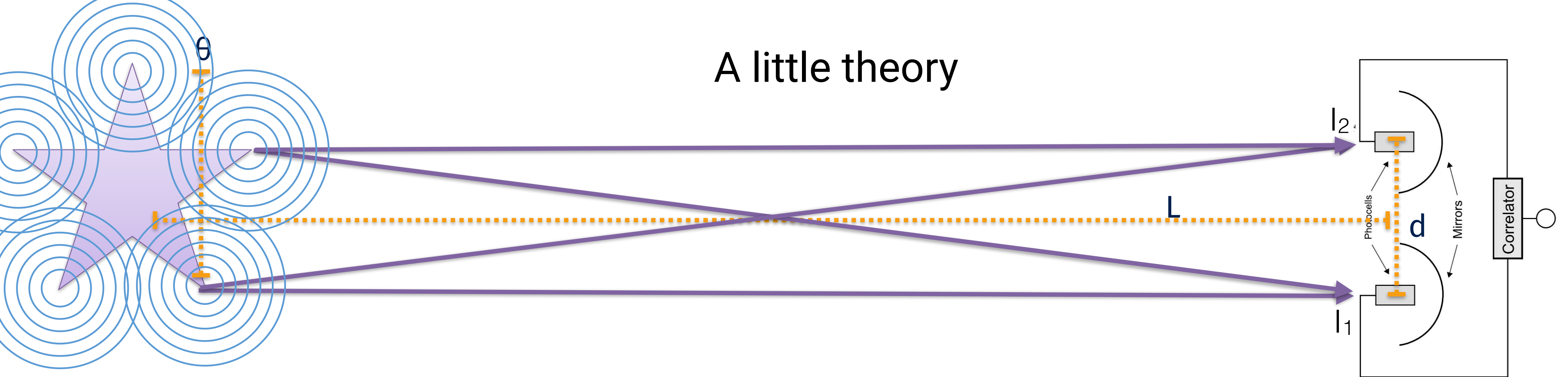
An extended body of angular diameter θ consisting of many incoherently emitting sources produces a speckled pattern at the observer of typical size λ/θ

A pair of observers separated by a distance ≪λ/θ are in the same speckle and ∴ see the same intensity fluctuations.

Observers separated by ≫λ/θ are likely to be in different speckles and see fluctuations with less or no correlation.

Measuring the scale at which the signals become de-correlated gives a measure of the angular size of the emission region.

$$\langle I_1(t) I_2(t) \rangle = \langle I_1(t) \rangle \langle I_2(t) \rangle (1 + |\Gamma_{12}(d)|^2)$$

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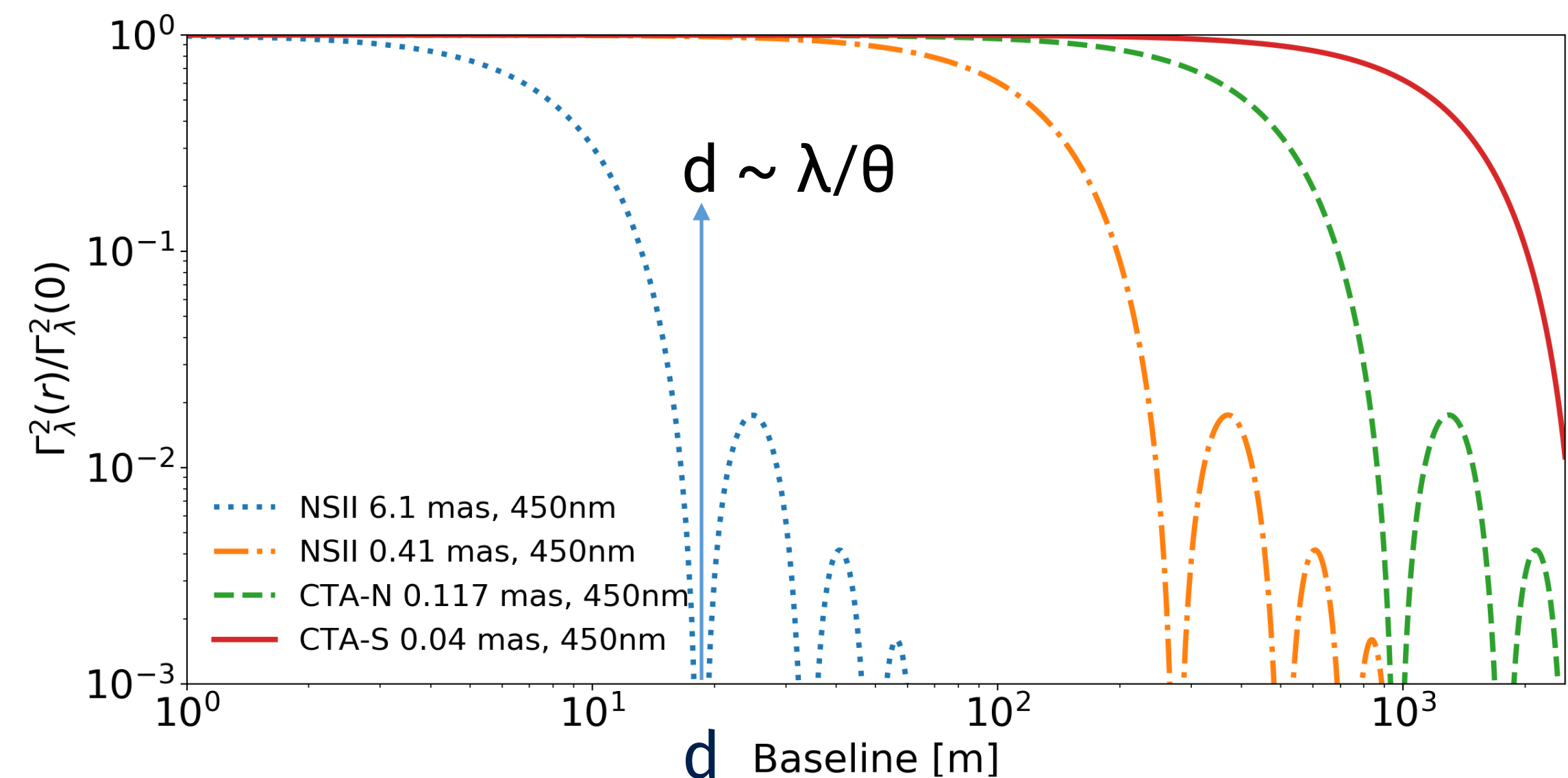
Second order time coherence g[(2)] & Fourier image plane

Van Cittert-Zernike Theorem $g^{(1)}(u,v,0) = \int\int I(l,m)e^{-2\pi(lu+mv)}\mathrm{d}l\mathrm{d}m$

image size & brightness distribution
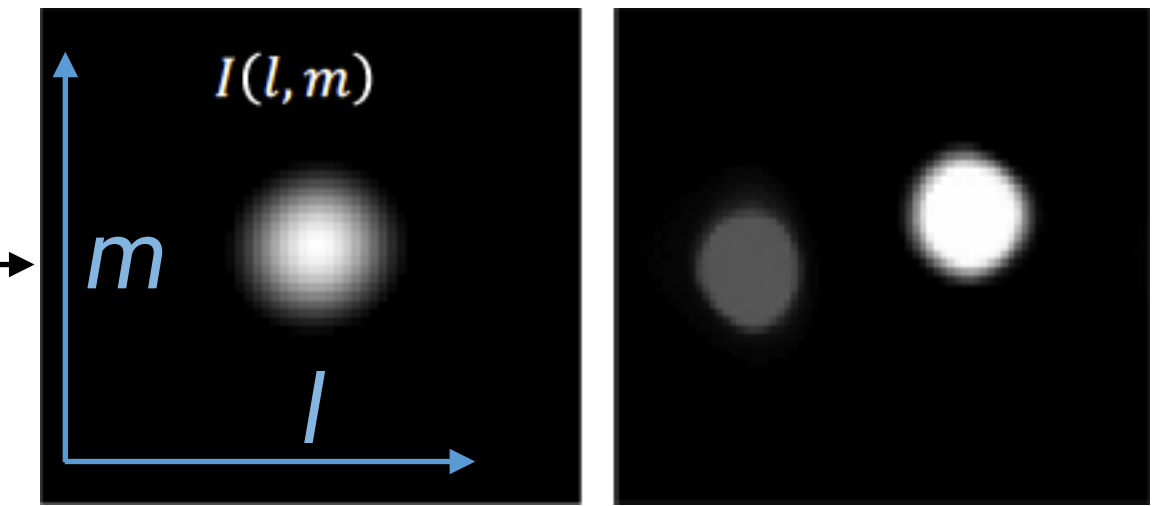
Matthews, Kieda & LeBohec *JMOp* **65**, 1336 (2018).

$$\frac{<I_1 I_2>}{<I_1><I_2>} = g^{(2)}(u,v,t) = 1 + |g^{(1)}(u,v,t)|^2$$

$g^{(2)}(0,0,0) = 1 + \varepsilon \sim 1 + 10^{-4}$ -> small non-Gaussian fluctuations requires large photon statistics, i.e. **large collecting surfaces**

Intensity fluctuations lose the phase information, but this can be recovered / compensated for

- e.g. Cauchy-Riemann algorithm Nuñez et al. MNRAS (2012).
- e.g. three point intensity correlations Nuñez & Domiciano de Souza MNRAS (2015).

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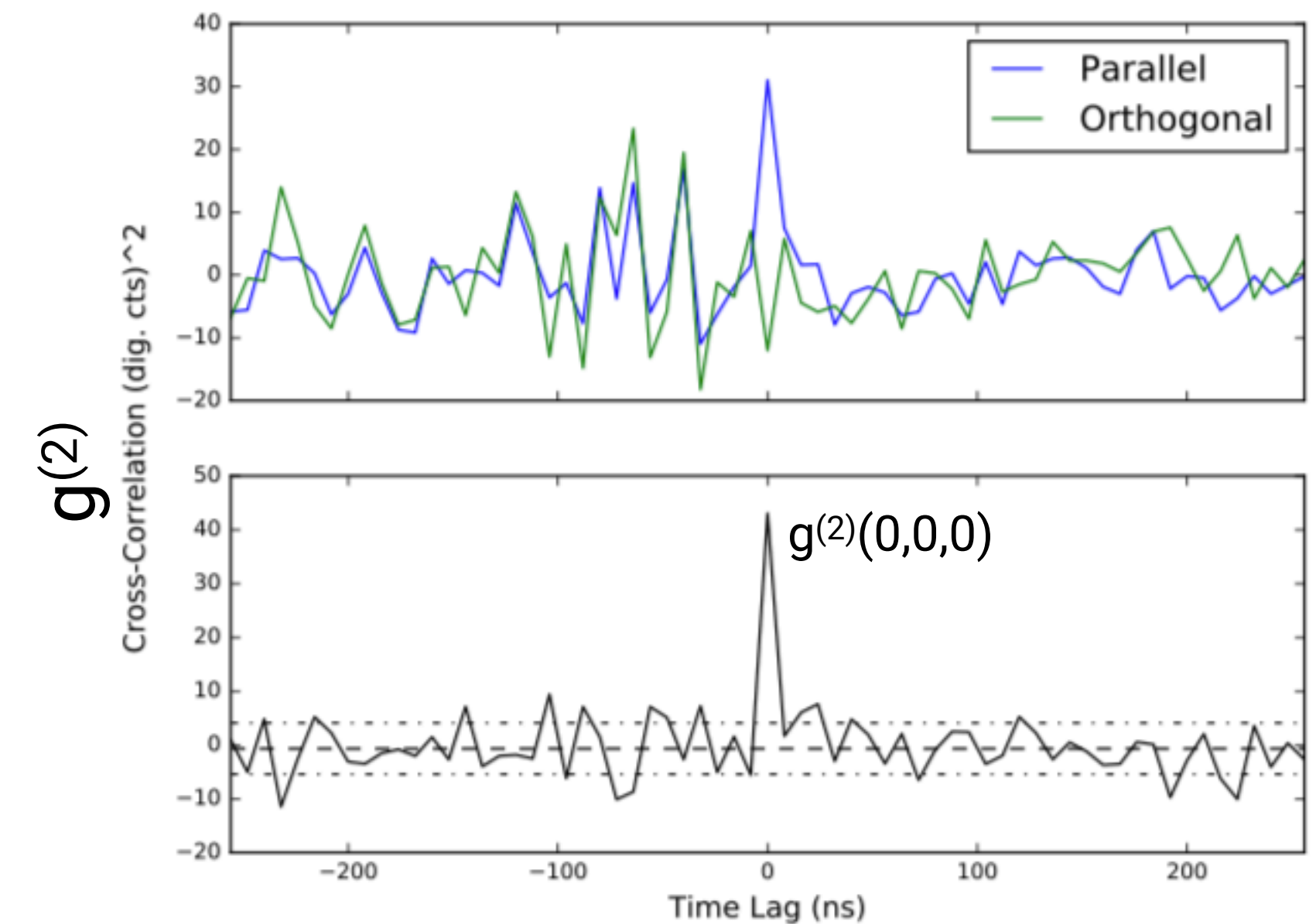
Narrabri Stellar Intensity Interferometer (NSII)

- 2x 6.5m dishes on a 188m diameter circular track
  - large mirror surface, with simple optics looks like an IACT.

- Measured angular diameter of 32 stars $-2 < m_v < 3$

  Hanbury Brown, Davis & Allen *MNRAS* **167**, 121 (1974)

- Directly measured limb darkening of Sirius

  Hanbury Brown, Davis Lake & Thompson *MNRAS* **167**, 475 (1974)

- Multiple stars & spectroscopic binaries (e.g. Spica/α Vir)

  Herbison-Evans, Hanbury Brown, Davis & Allen *MNRAS* **151**, 161 (1971)

- Emission line regions around a star (γ Velorum)

  Herbison-Evans, Hanbury Brown, Davis & Allen *MNRAS* **148**, 103 (1970)

The Intensity Interferometer
its applications to astronomy
Hanbury Brown (1974)

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HARVARD & SMITHSONIAN
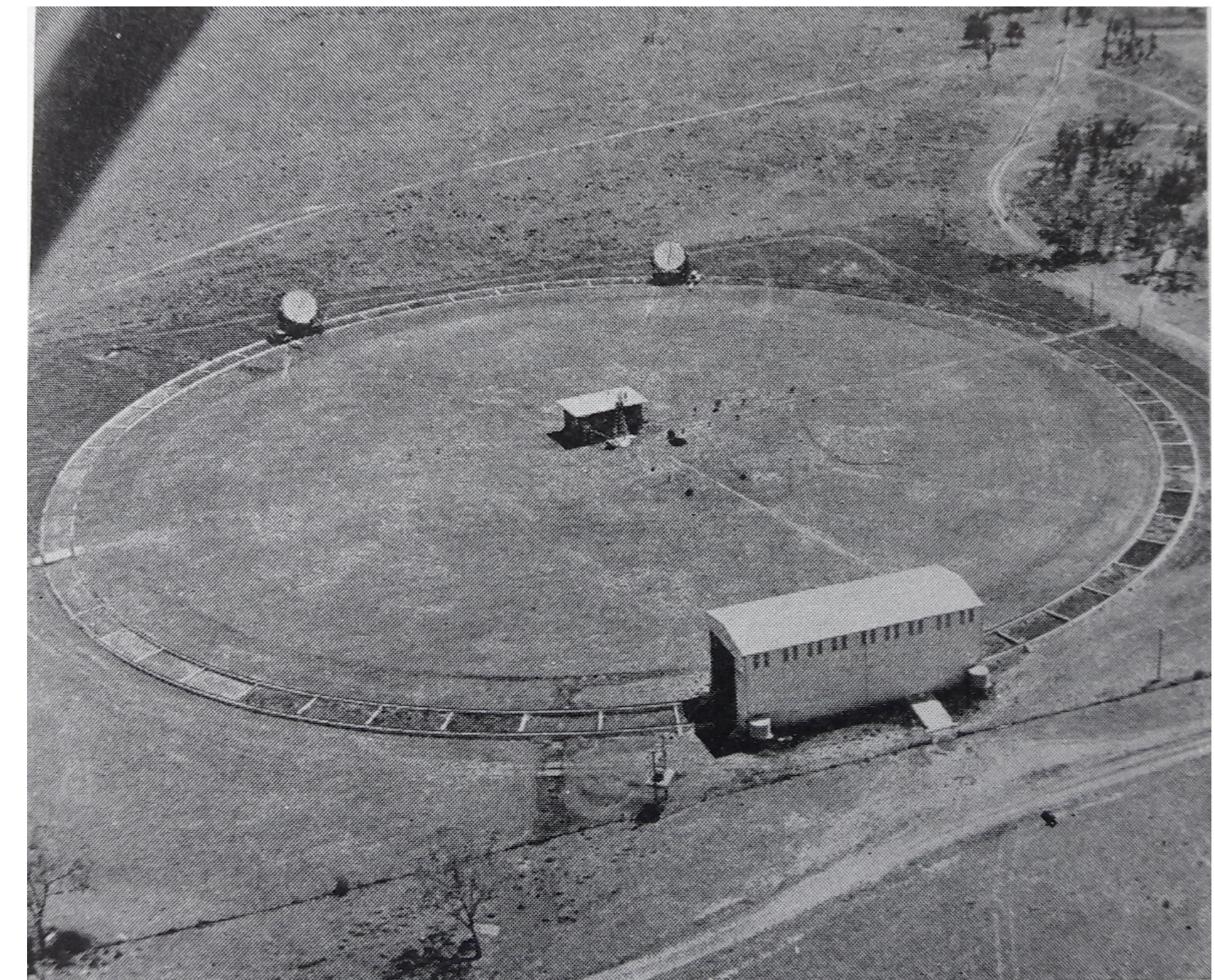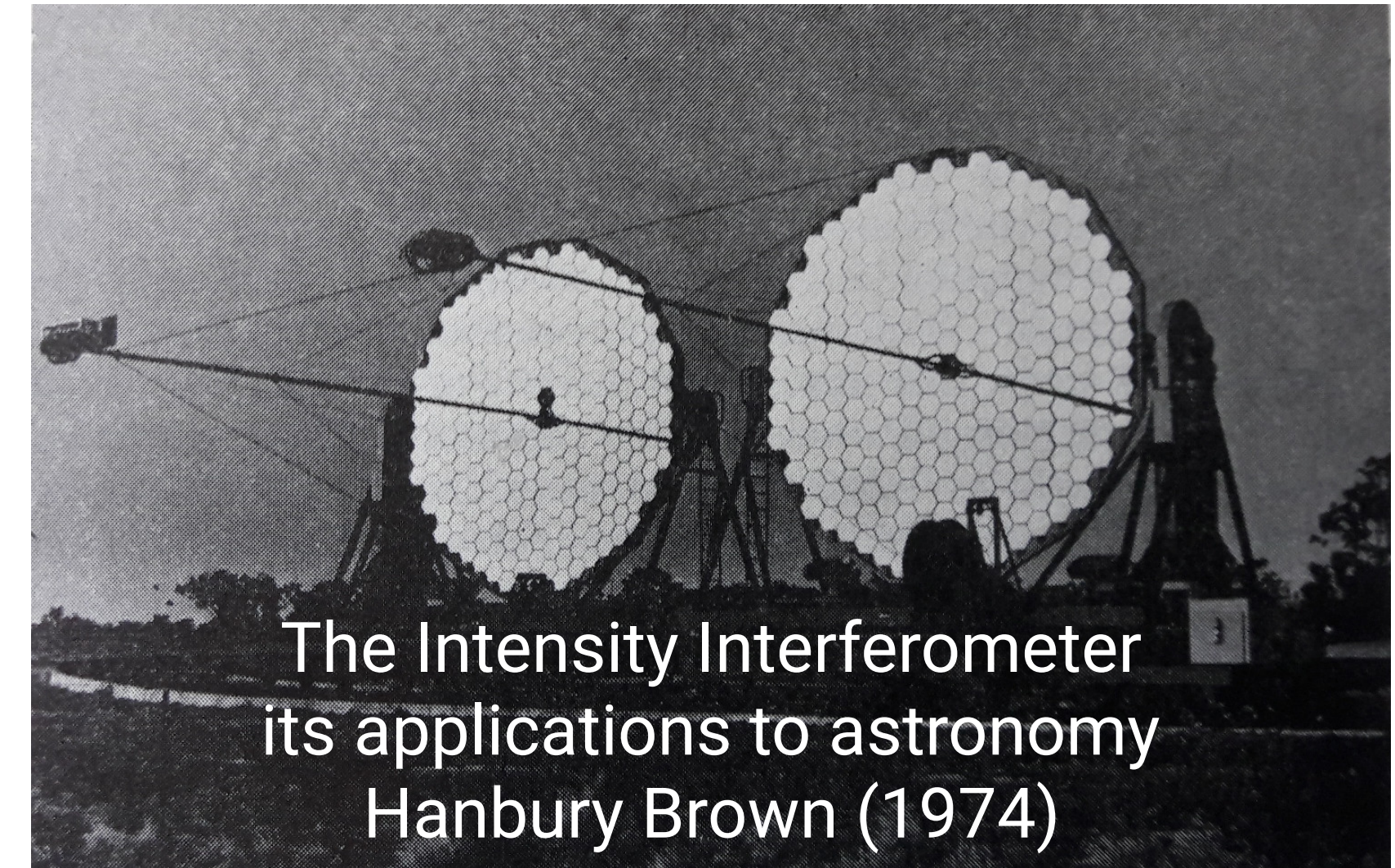
Stellar intensity interferometery at VERITAS

See poster PS1-76 (session 1)

- 4x 12m diameter telescopes, arranged on rectangular grid of ~100m

- Equipped VERITAS for SII observations (augmentation funded by an NSF-AST RAPID grant)

  - beginning October 2018 (2 telescopes)

  - 3 telescope observations began in February 2019

  - measures photon intensity at each telescope with continuous digitization directly to disk (correlation is offline)

- Goal: image ~30 nearby stars in U/V band

  - observe ±2 days from full moon (when gamma-ray observations not scheduled)

  - not a problem for bright (m<4) sources with suitable filters

Kieda (2019)

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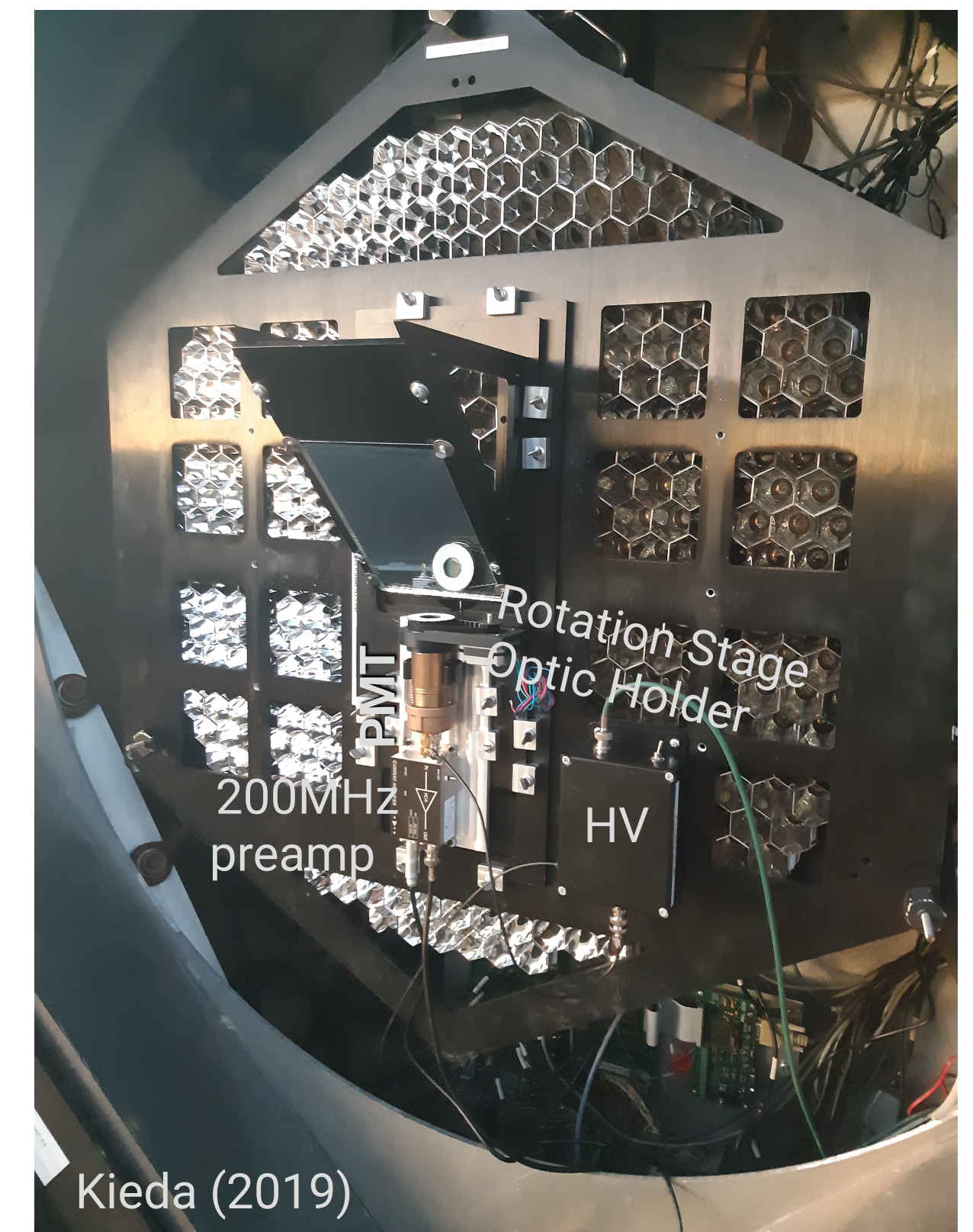
First Observations/ Results

2 telescope results

Betelgeuse

Bellatrix

γ Ori

Barnard's Loop

Orion's Belt

Orion Nebula

Saiph

κ Ori

Rigel

APOD

γ Ori

Preliminary

multiple points as apparent baseline changes as target moves across sky
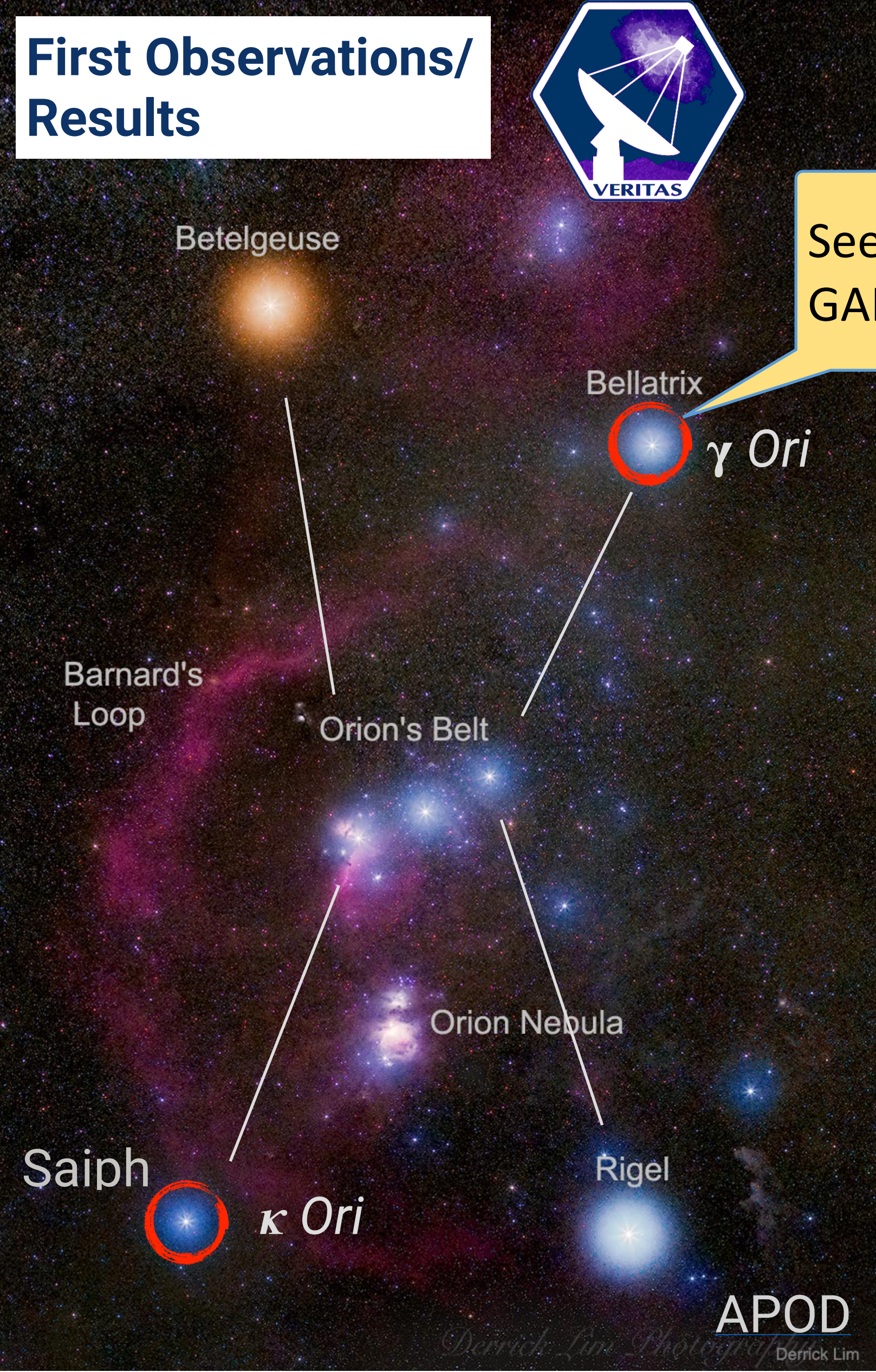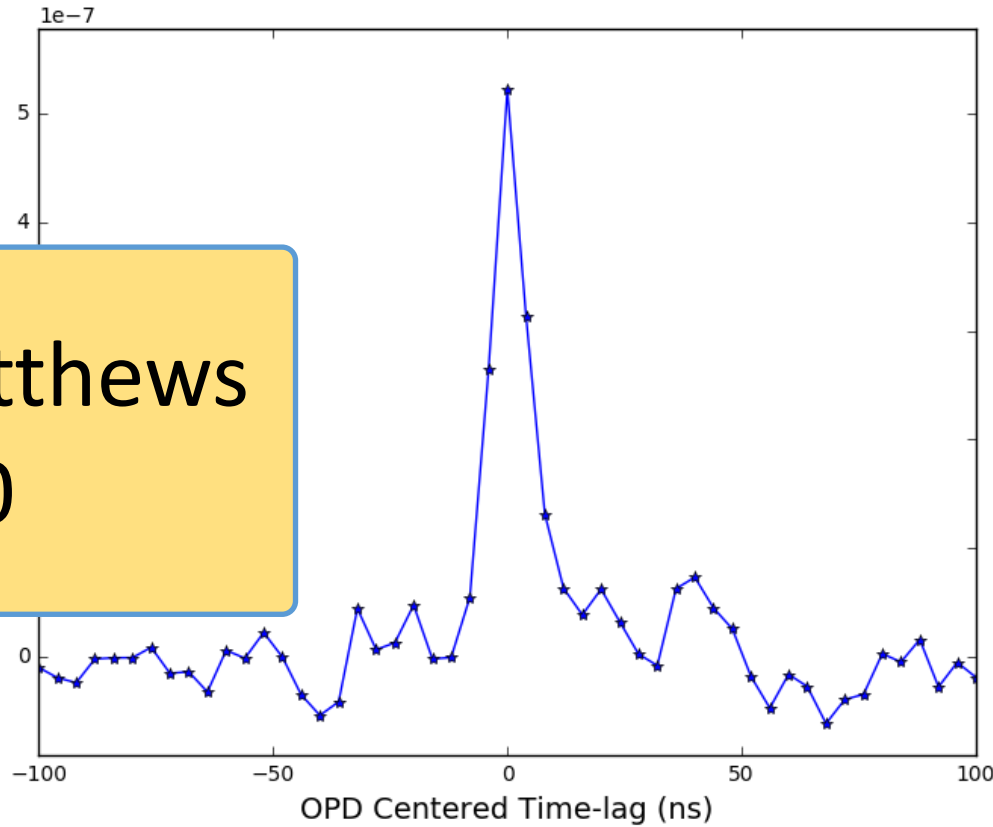
- Data taken in 20m 'runs'

- Streamed to disk (@250MS/s)

- Correlated offline next day

  - next step, perform higher order correlations with more telescopes (phase recovery).

	T_{obs} [h]	θ_{meas} [mas]	cf θ_{UD} [mas]
γ Ori	4.74	0.68 ± 0.06	0.701 ± 0.005
κ Ori	5.13	0.48 ± 0.06	0.44 ± 0.03 Richichi et al (2005)

κ Ori

Preliminary

$$\left[\frac{2J_1(x)}{x}\right]^2$$

$$x = \pi d\theta_{UD}/\lambda$$

Matthews (2019)

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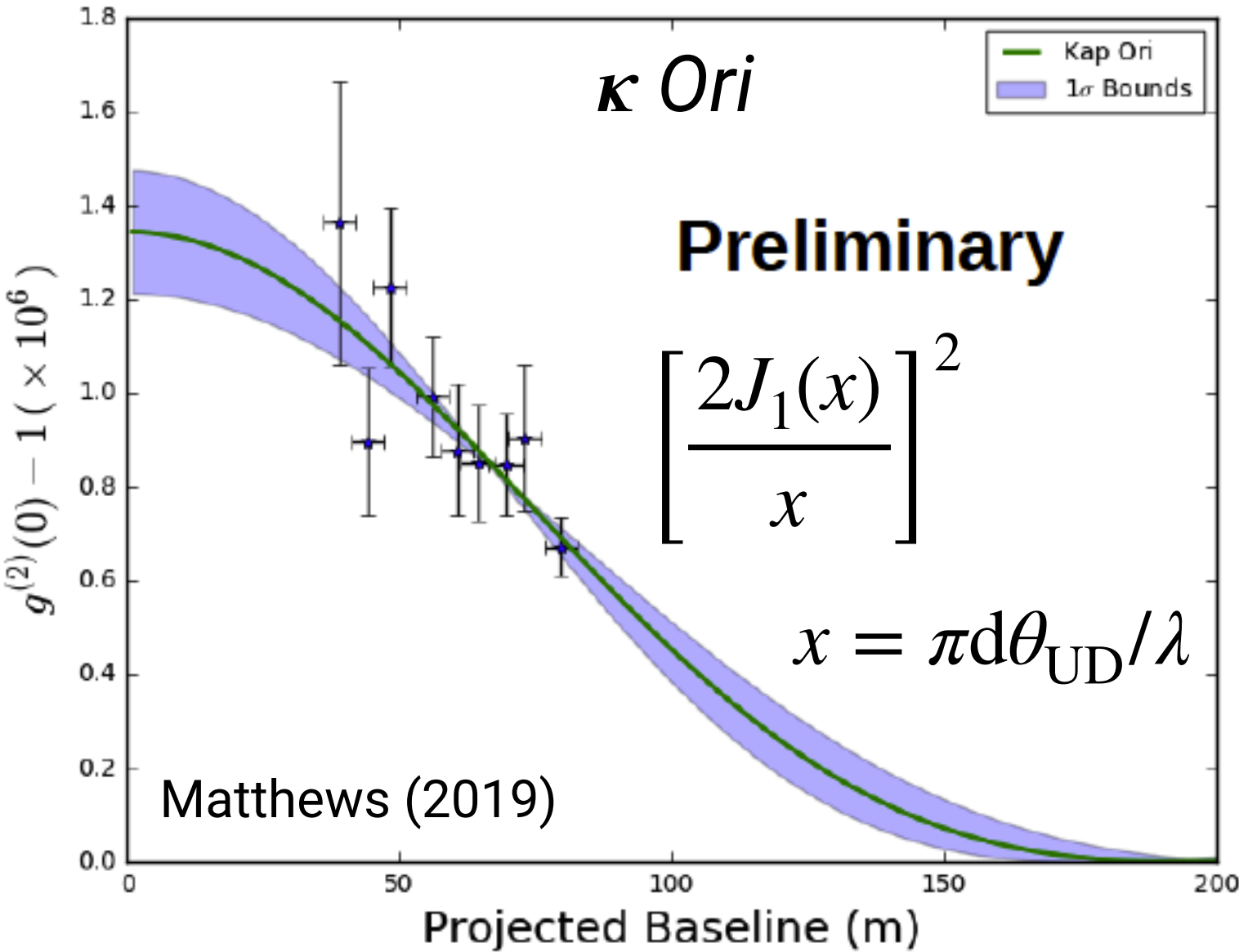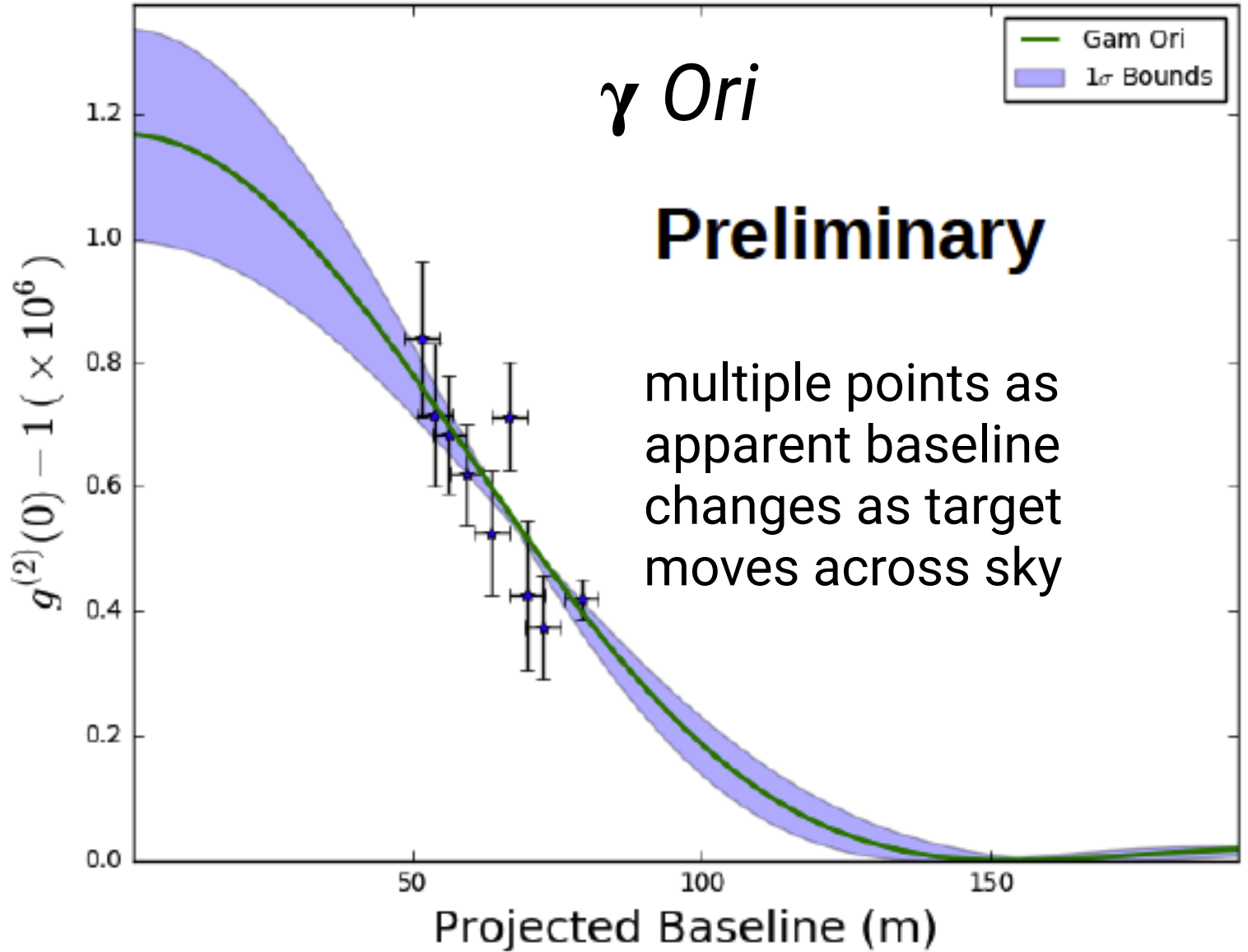
Stellar angular diameters measured by intensity interferometry and asteroid occultations

How does an IACT compare?

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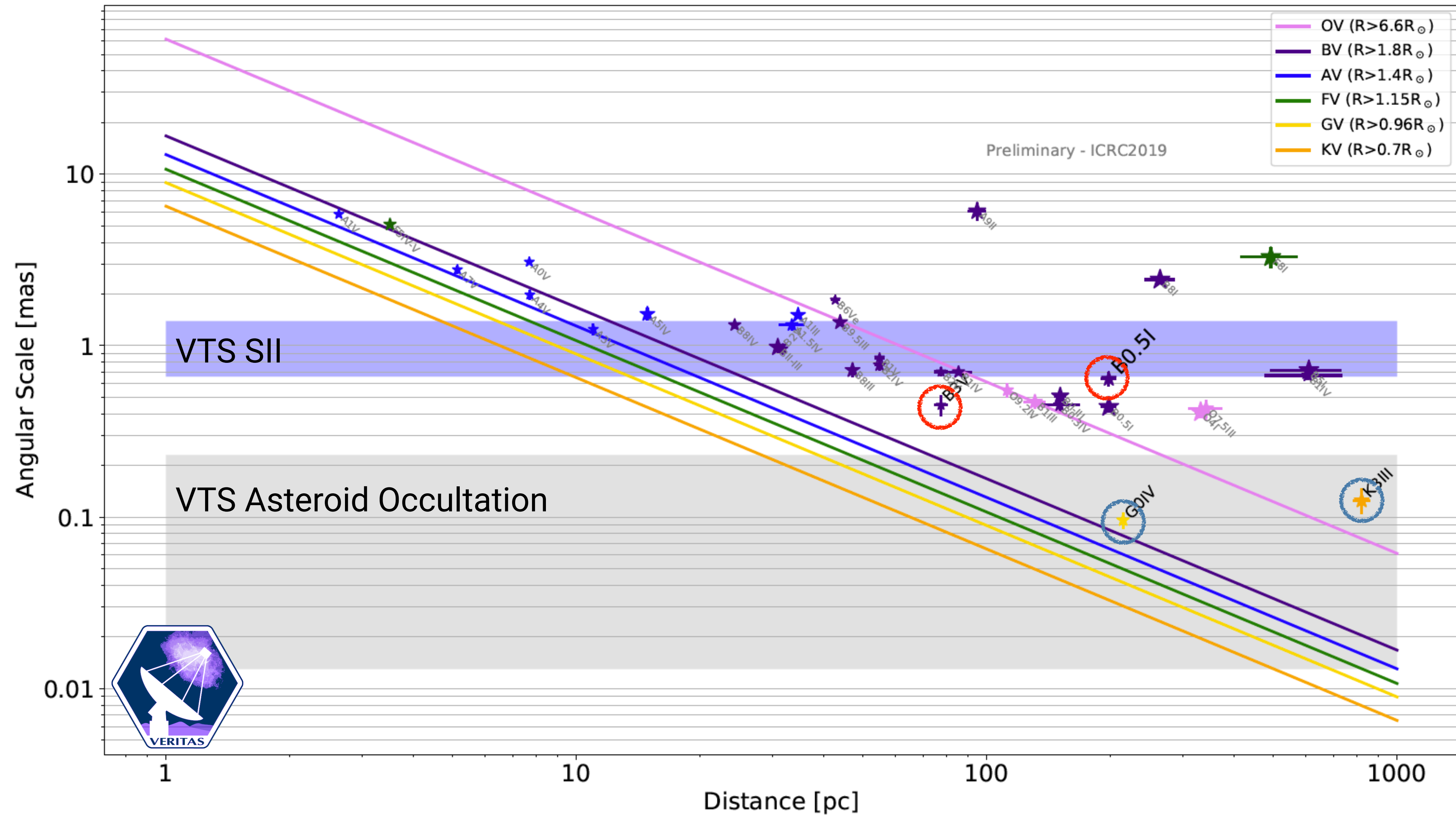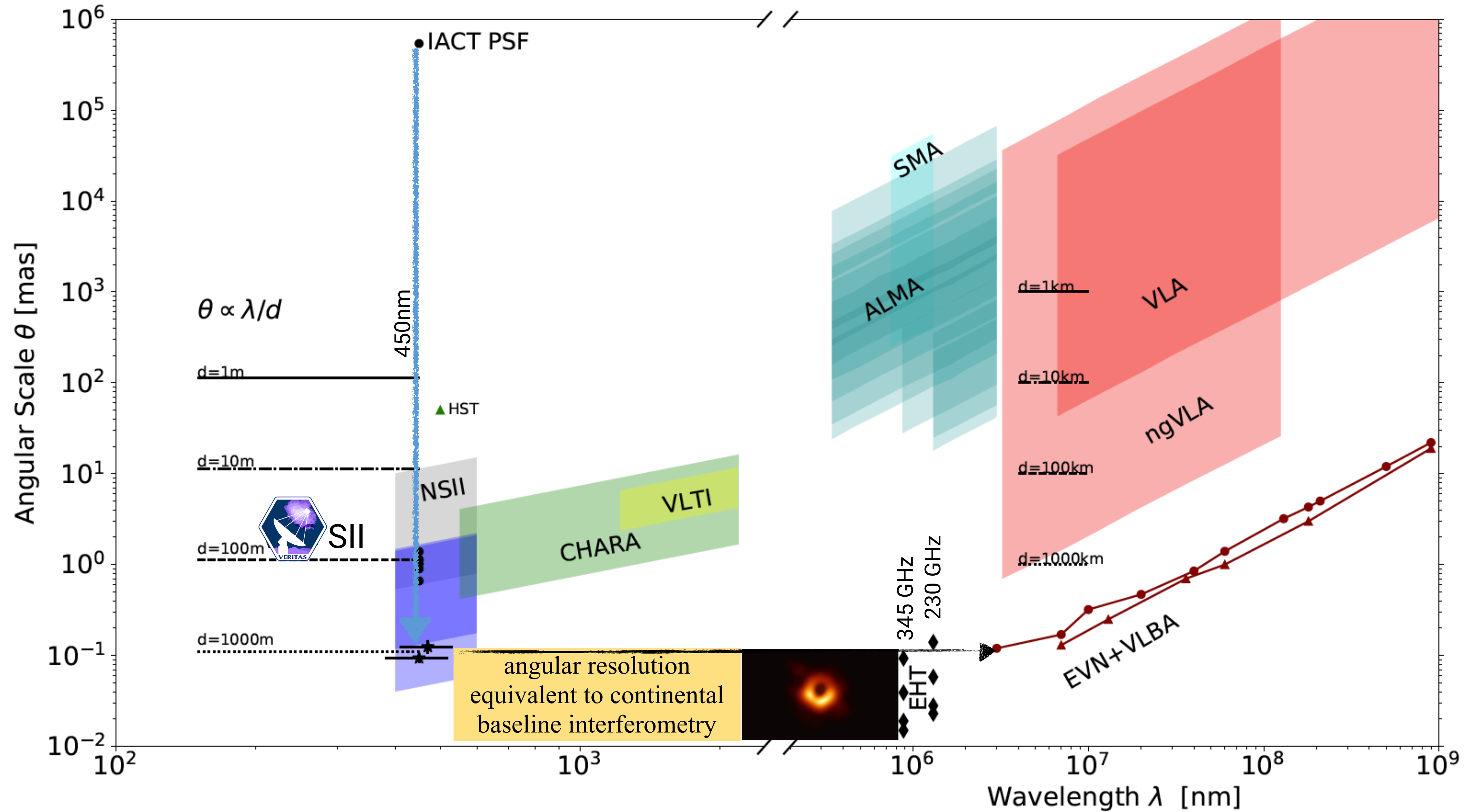
A lot of science…

in a short space of time

- angular diameters
- limb darkening
- rapid rotators
- binary systems
- emission line regions
- star spots
- …

see also, e.g.

Hanbury Brown (1974)
Barbieri et al Astro2010 paper 61, arXiv:0903.0062
Dravins et al *NewAR* **56**, 143 (2012).
Dravins et al *APh* **43**, 331 (2013).
Kieda et al Astro2020 paper ID 304 (2019).

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The first dimension — angular size of stars - uniform disc
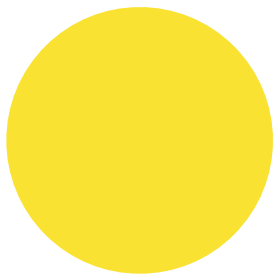
The larger the baselines, the smaller the detail we can see
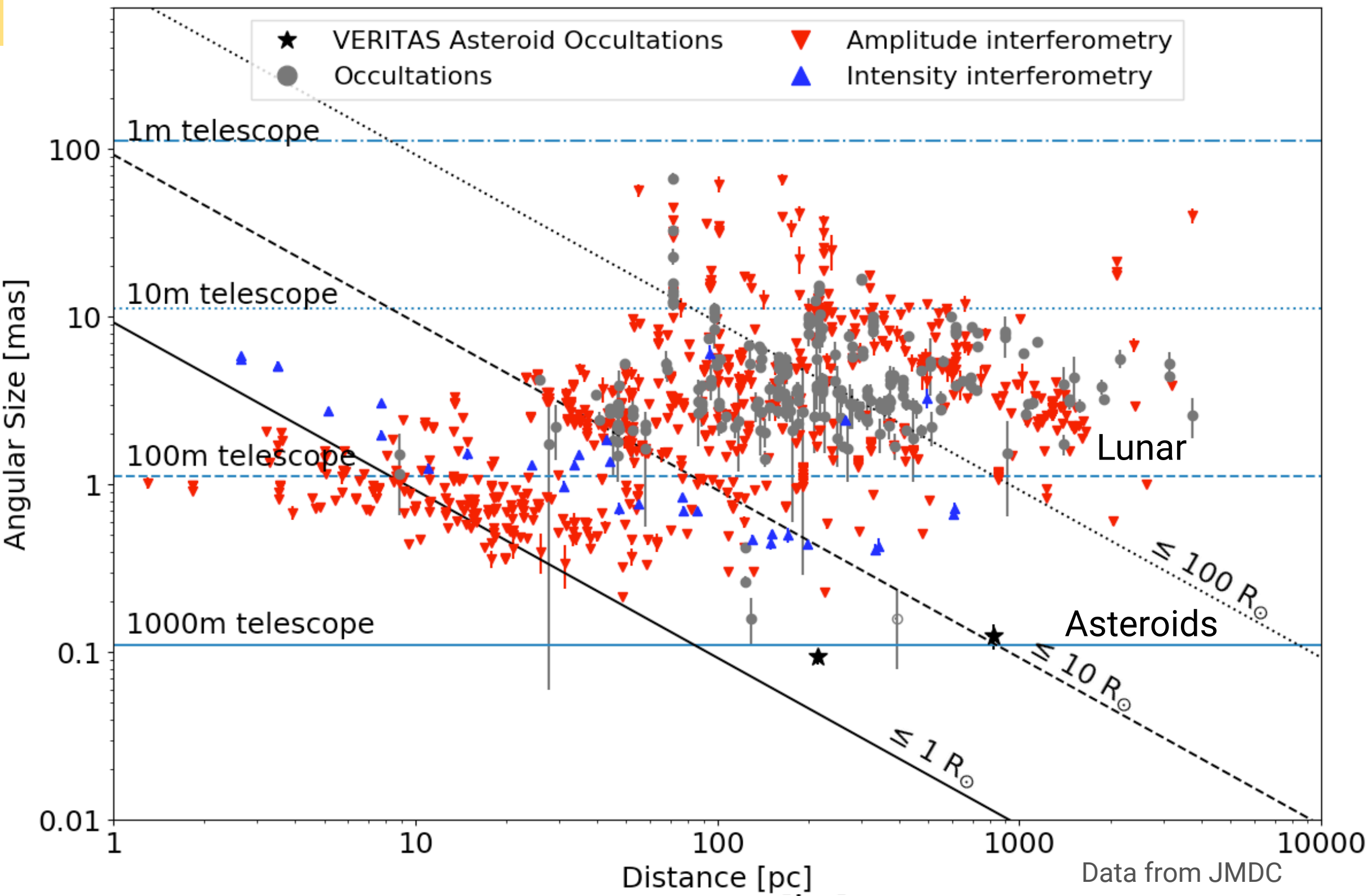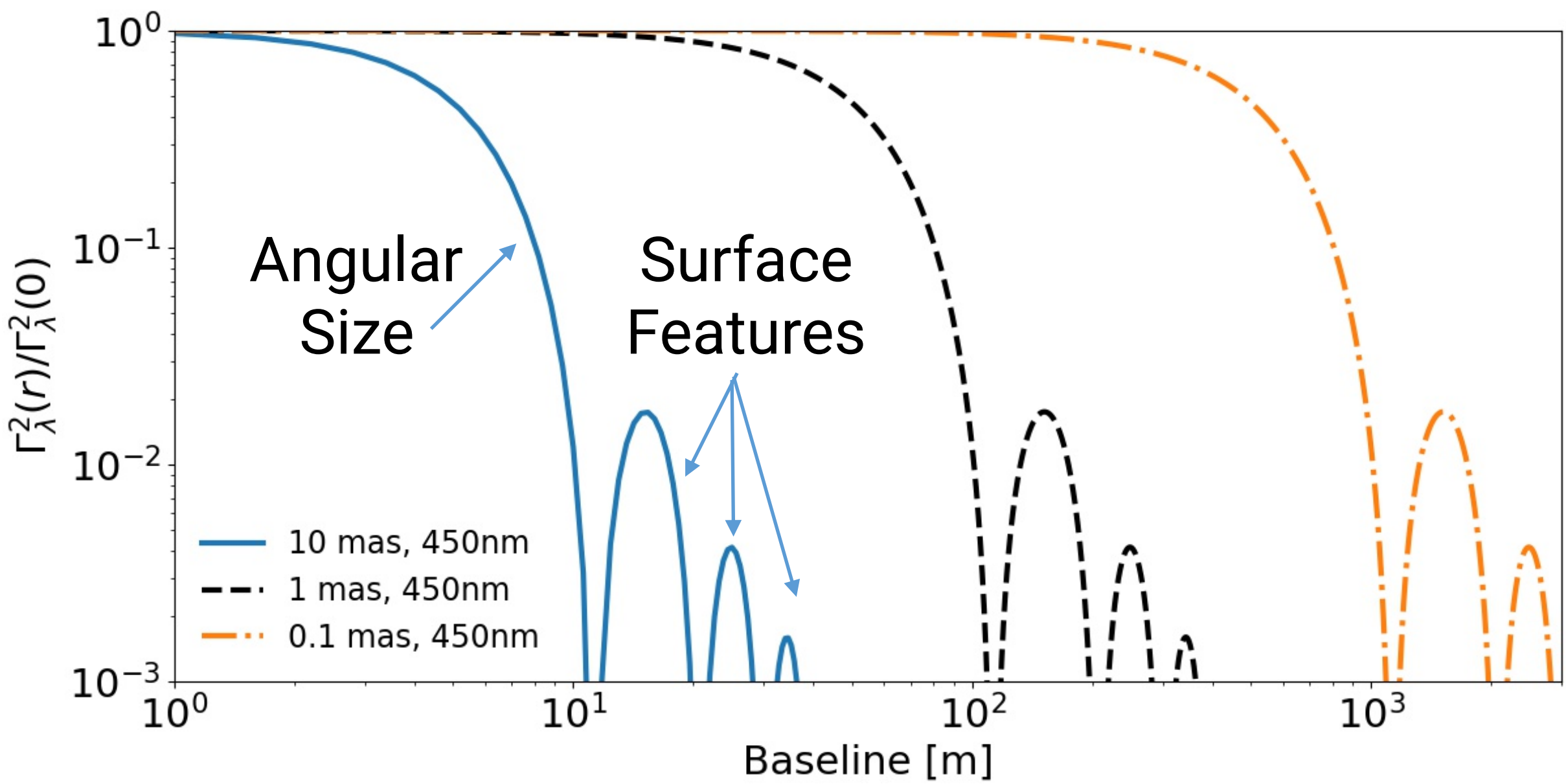
- Constrain stellar evolution models
- Also useful in determining size of transiting exo-planets

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The next dimension — limb darkening
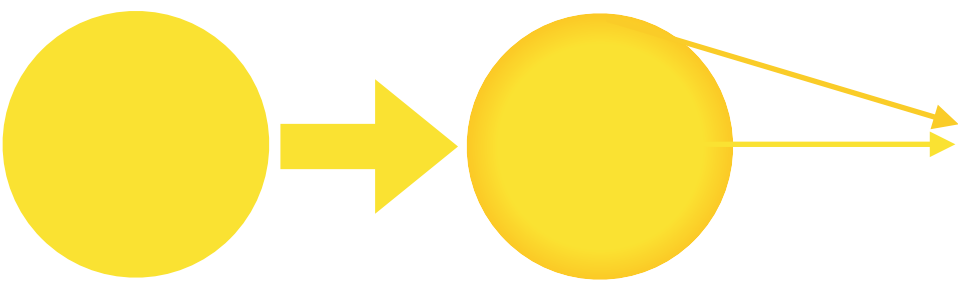
The longer the baselines, the more sensitive the observation... the more:
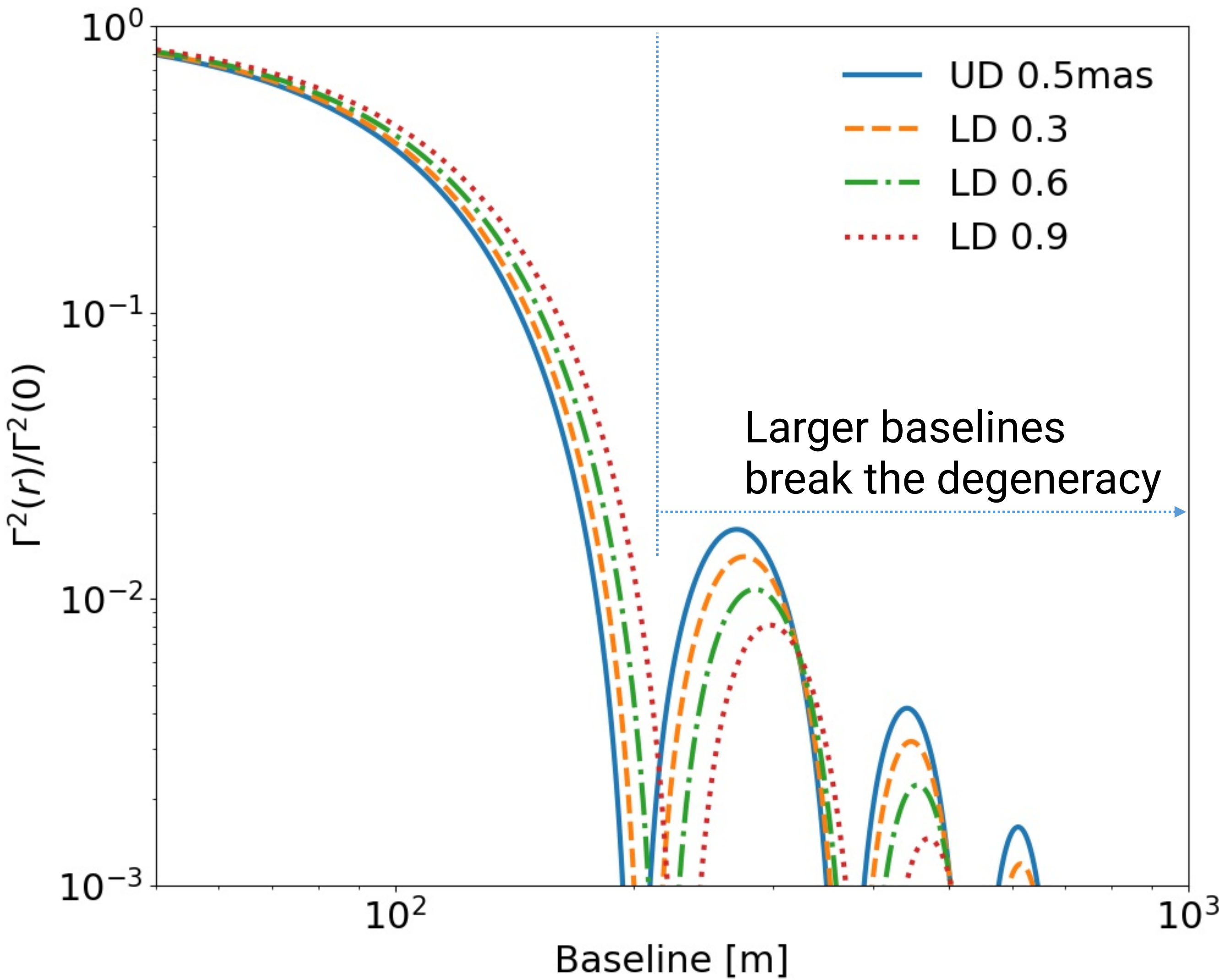
- **accurately** constrain stellar evolution models in a model independent way
- for <5% error can **accurately** determine size of transiting exo-planets
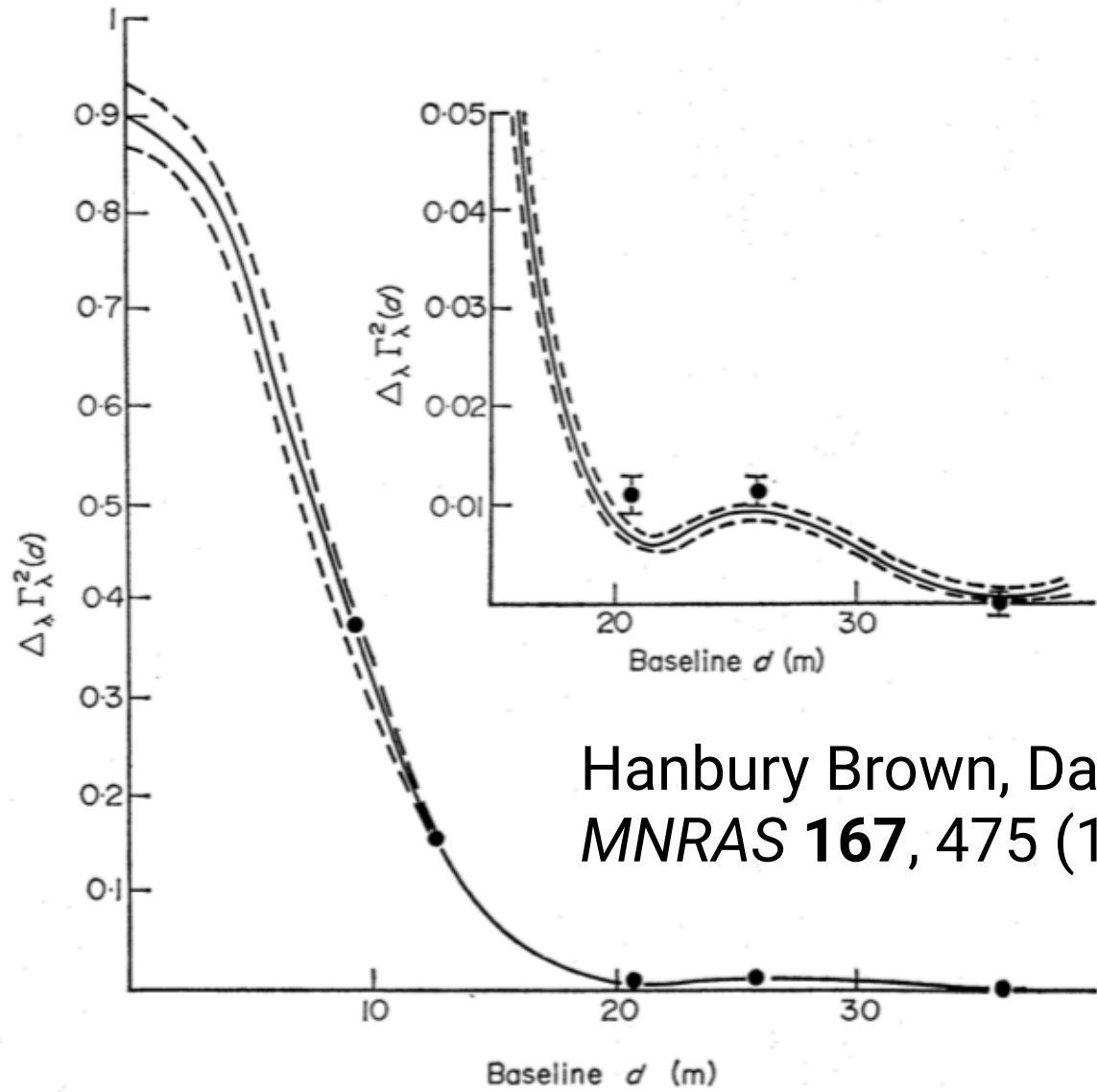
FIG. 3. *The variation of correlation $\Delta_\lambda\Gamma_\lambda(d)$ with baseline d for Sirius. The points show the observed values; the full line is a theoretical curve, based on a model stellar atmosphere ($T_e = 10\,000K$, $\log g = 4$), with zero-baseline correlation and angular size adjusted to give the best fit to the observations. The broken lines represent the rms uncertainty in the theoretical curves.*

Hanbury Brown, Davis Lake & Thompson
MNRAS **167**, 475 (1974)

Larger baselines break the degeneracy

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Rapidly rotating stars — distorted discs — gravitational darkening — e.g. Altair

- Be star disk formation
- winds from hot stars
- Wolf-Rayet star environments
- GRB pre-cursors
- …

Altair w/ 18m baseline — NSII

See how the correlation changes with time (i.e. position angle to stellar axis)

Hanbury Brown (1974)
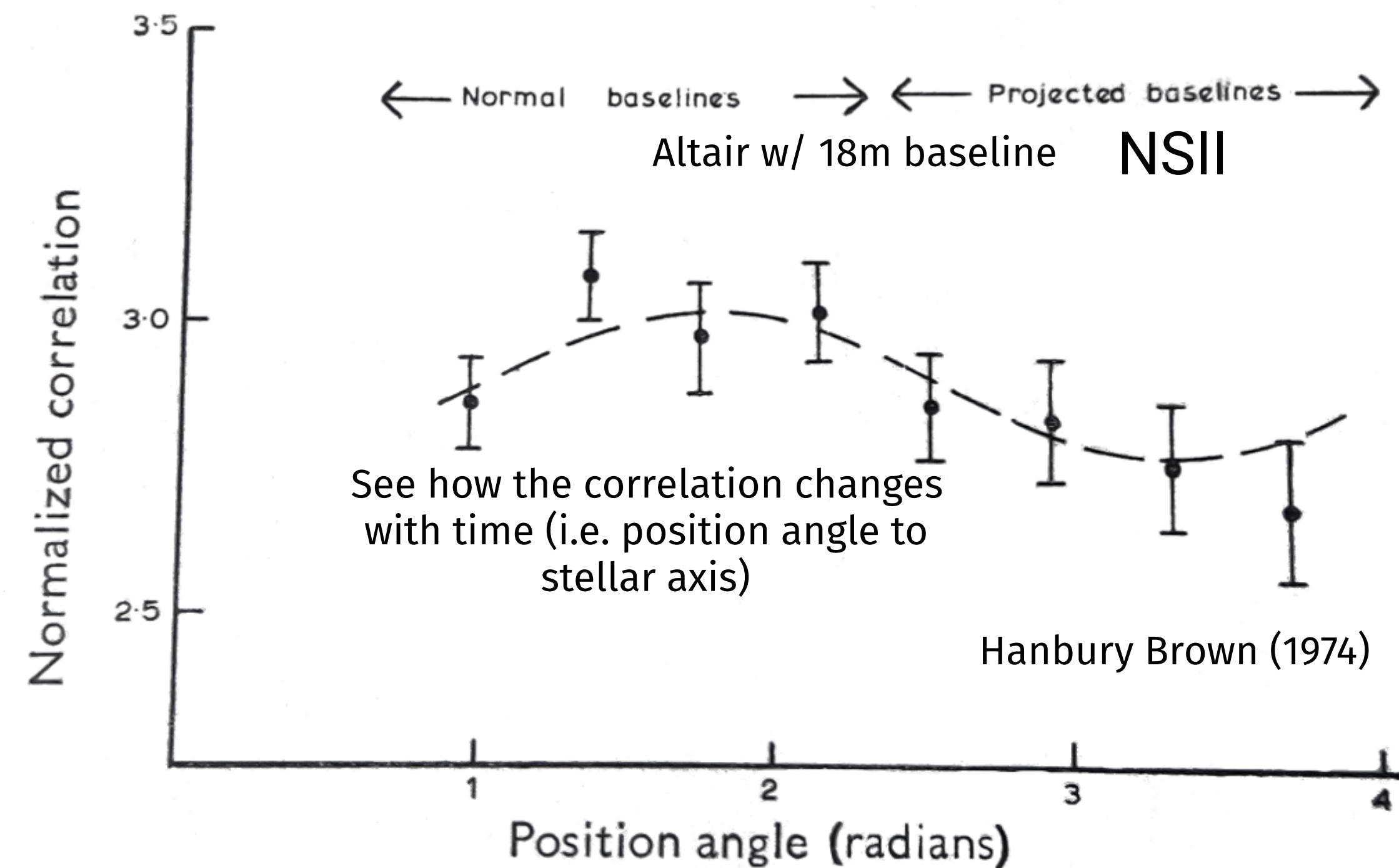
with 2 telescopes…   *get an impression*

With more telescopes we provide the data to fit a model to, rather than vice versa

A Altair Image Reconstruction — CHARA

B High-Fidelity Image — Convolving Beam (0.64 mas)
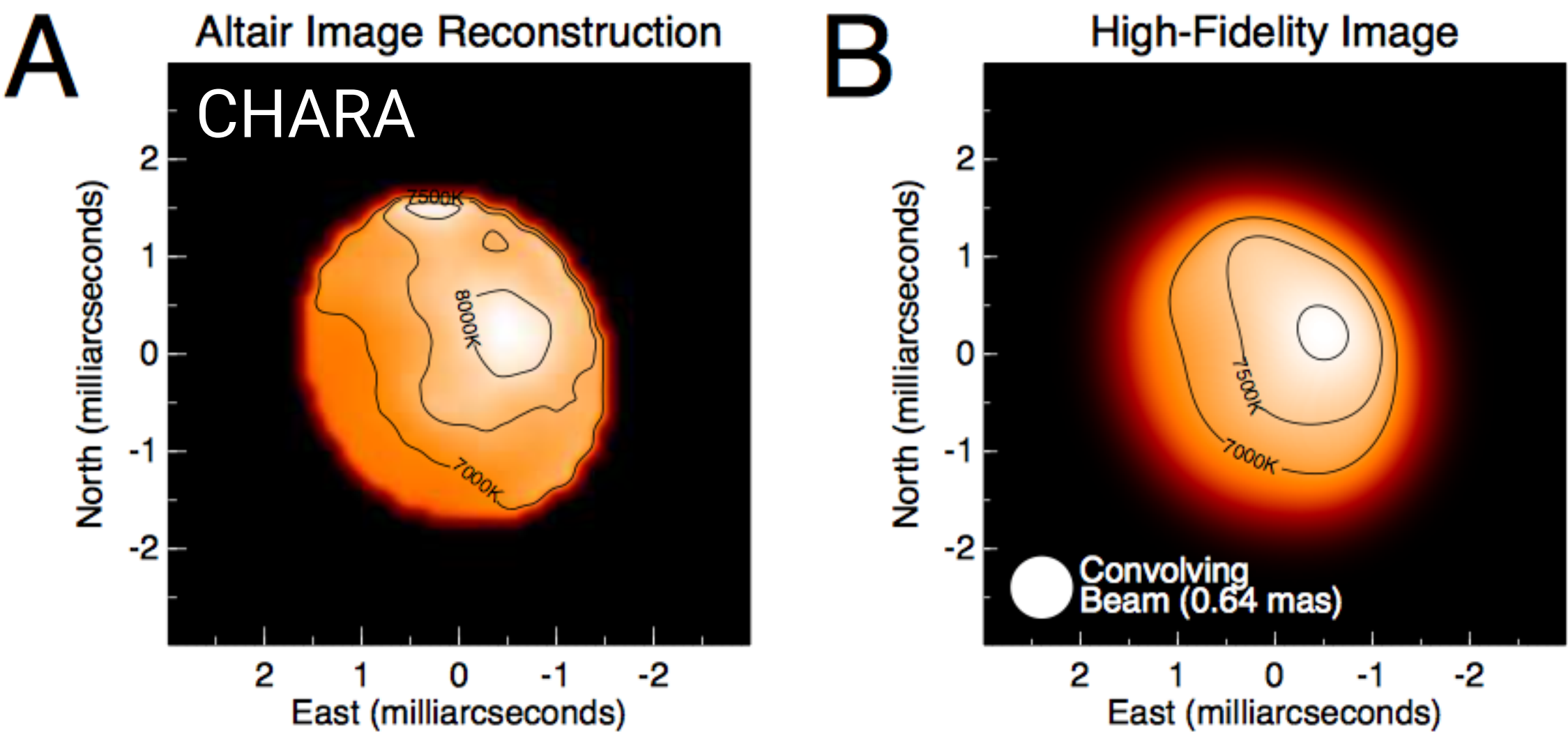
with 6 telescopes…   **start to build a picture**

The difference between the CHARA observation and the theoretical model "shows stronger darkening along the equator, inconsistent with any von Zeipel-like gravity darkening prescription assuming uniform rotation."

CHARA *Science* **317**, 5836 (2007)

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Binary systems & star spots & accretion zones …

Remember, these are dynamic systems.

A time averaged correlation provides some information,
a time sequence or series of images provides more

So requirements are:
▸ Many baselines of >100m
▸ Many baselines measuring simultaneously for shorter observation times
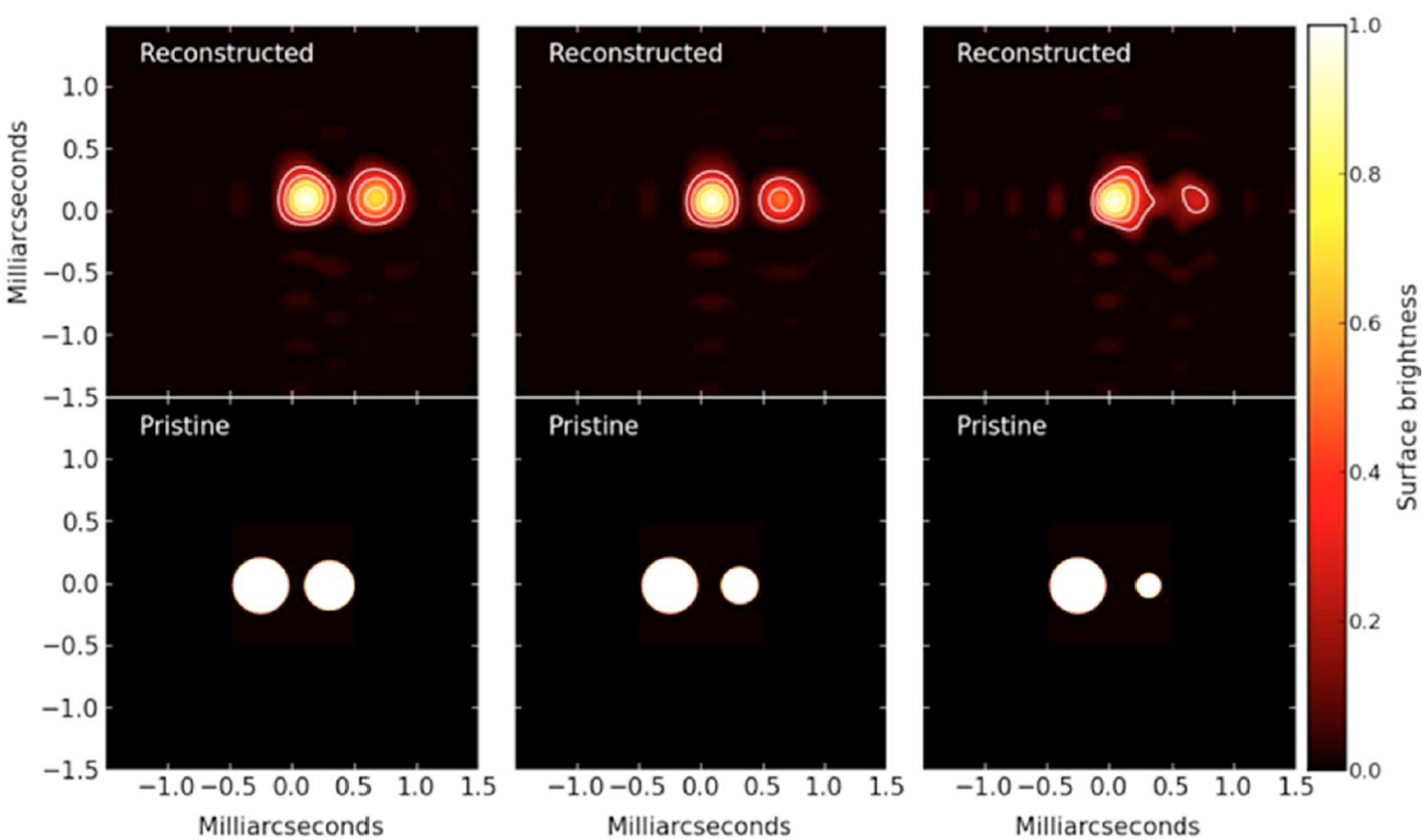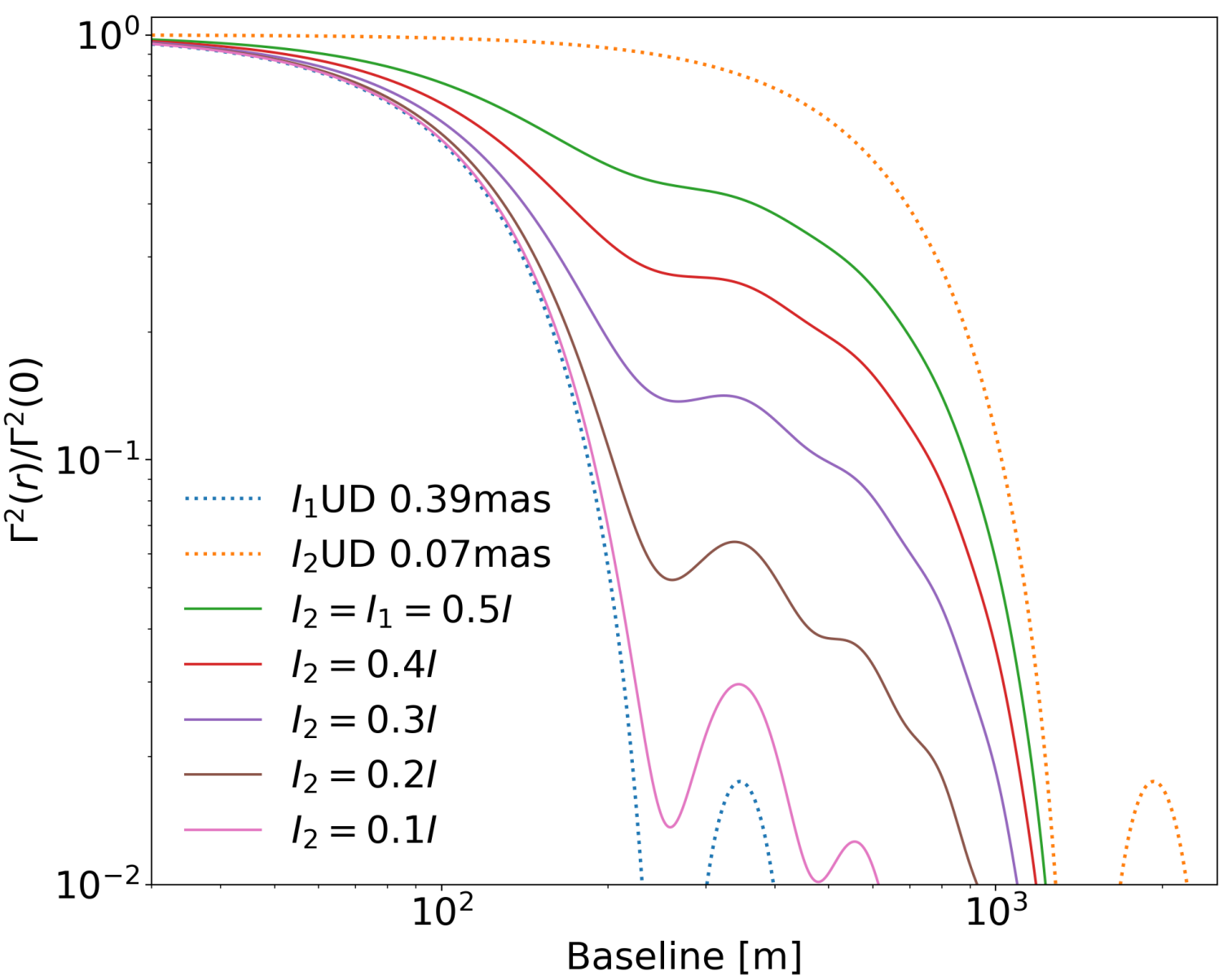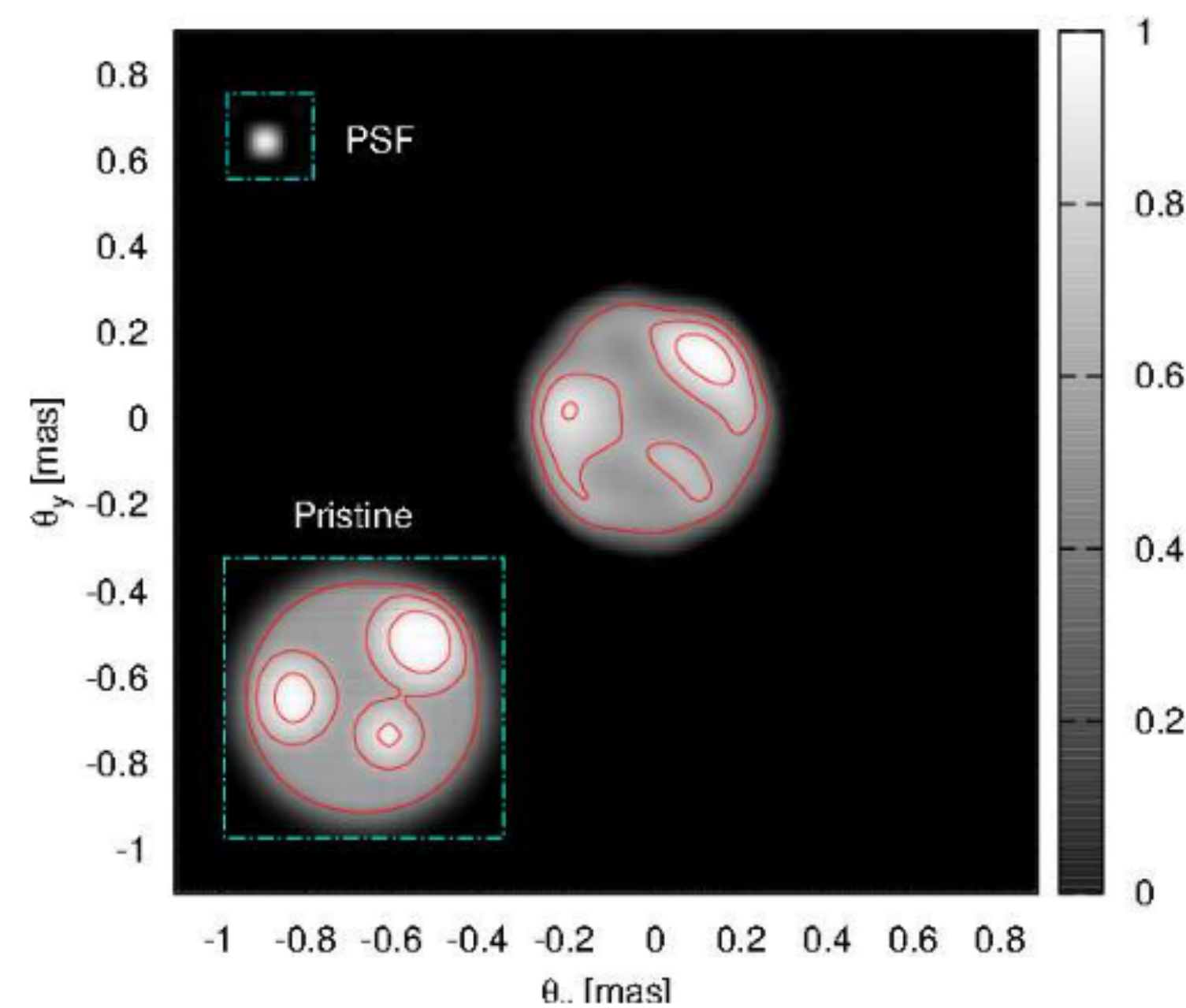
Figure 5: Reconstructed images of binary stars (with varying diameter of the secondary) from simulated CTA observations. These simulations were for the array layout B (Figure 2), for sources assumed to have visual magnitude $m_V = 3$, and effective temperature $T_{eff} = 7000\,\mathrm{K}$. The assumed pristine images are shown below while the corresponding (u,v)−plane coverage is in Figure 6.

APh **43**, 331 (2013).

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A big future...

$$N_{pairs} = \frac{N_{tel}(N_{tel} - 1)}{2}$$

# telescopes	2	5	15	25	50	100
# baselines	1	10	105	300	1225	4950

With so many available baselines **model independent** imaging becomes a realistic possibility

~km

46
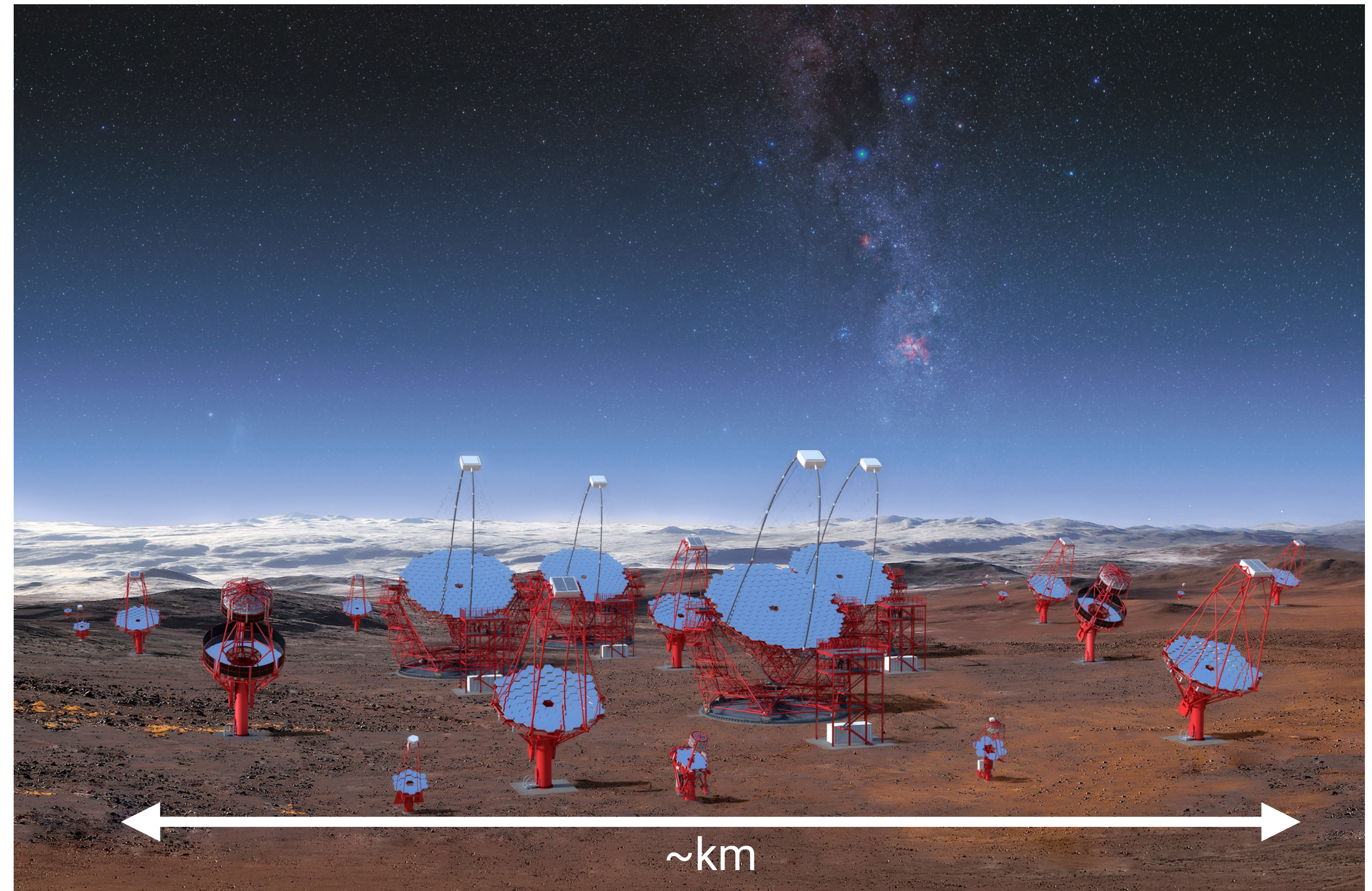
More than one-dimension: imaging with optical aperture synthesis

Model Image

Take a few telescopes
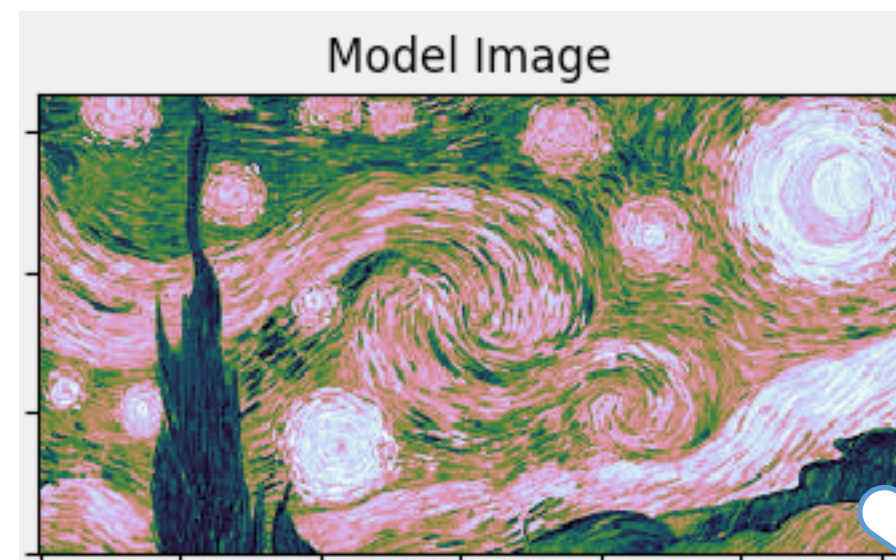
Source tracks through the sky increasing number of available baselines.
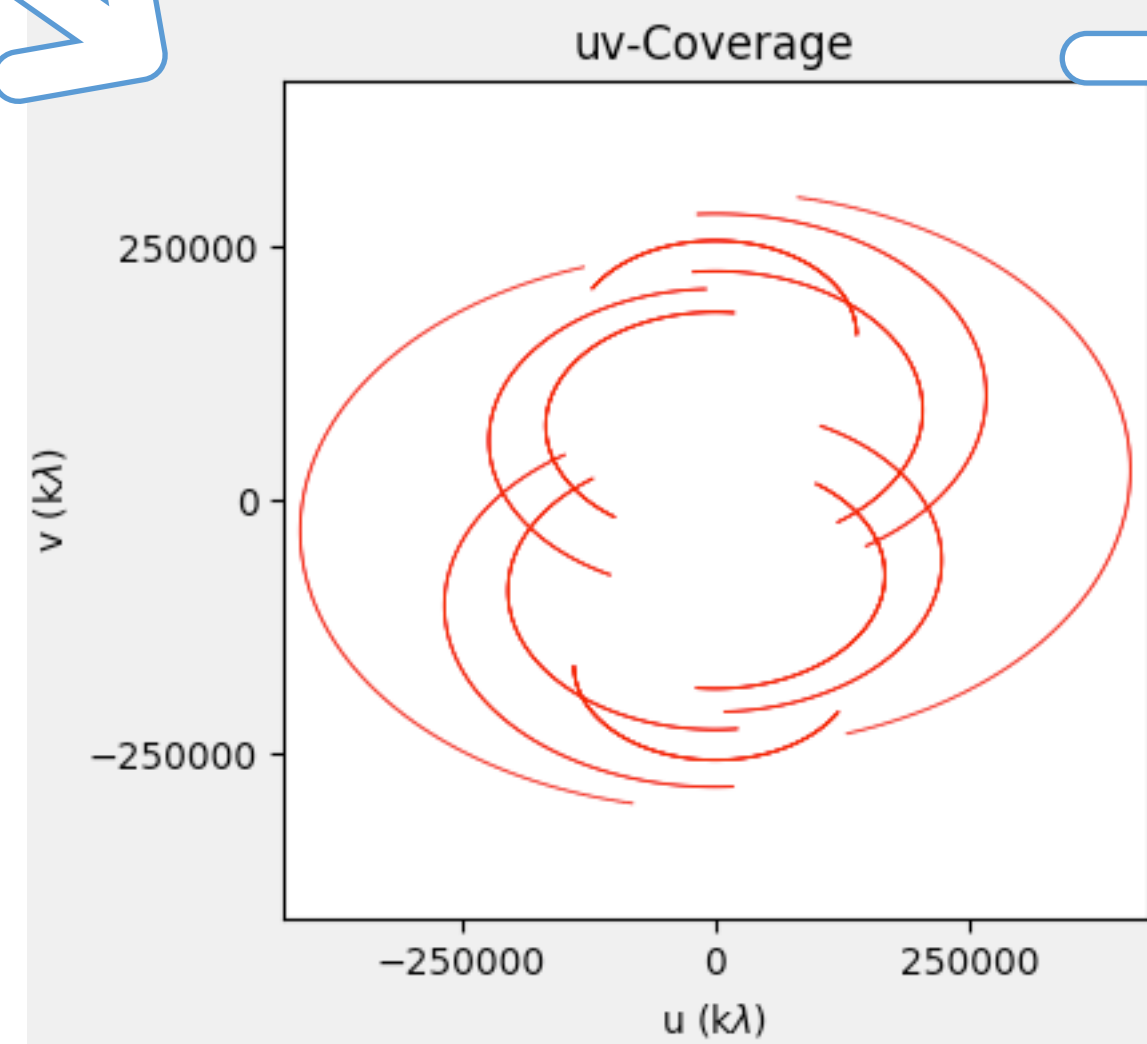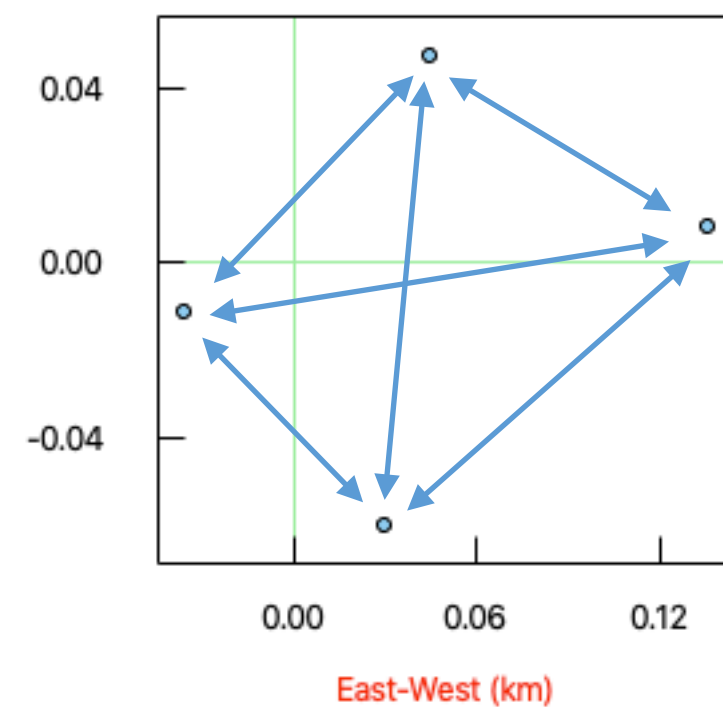
Sampling more of the Fourier spatial distribution of the observed target brightness.

Observed Image

uv-Coverage

Observed FFT
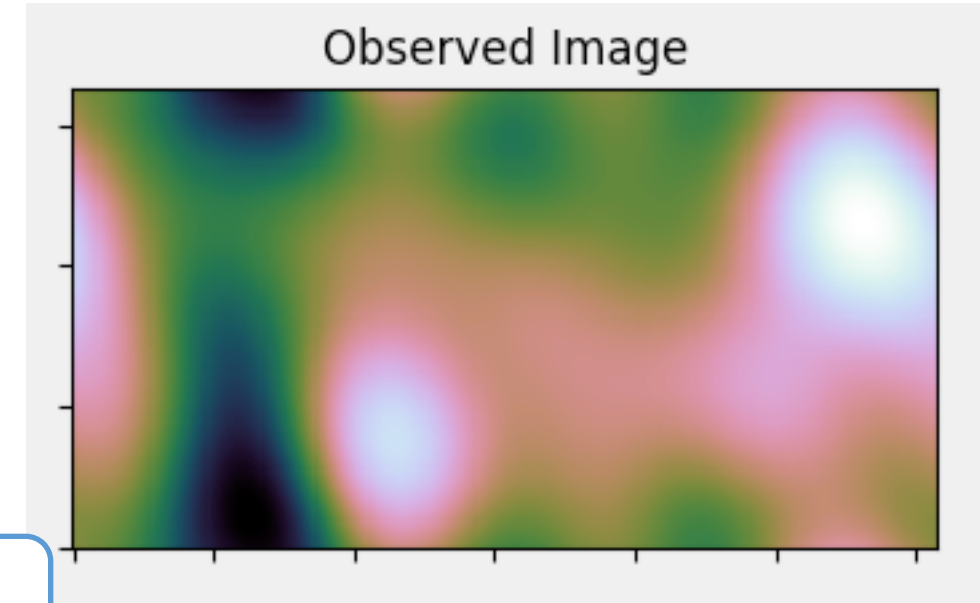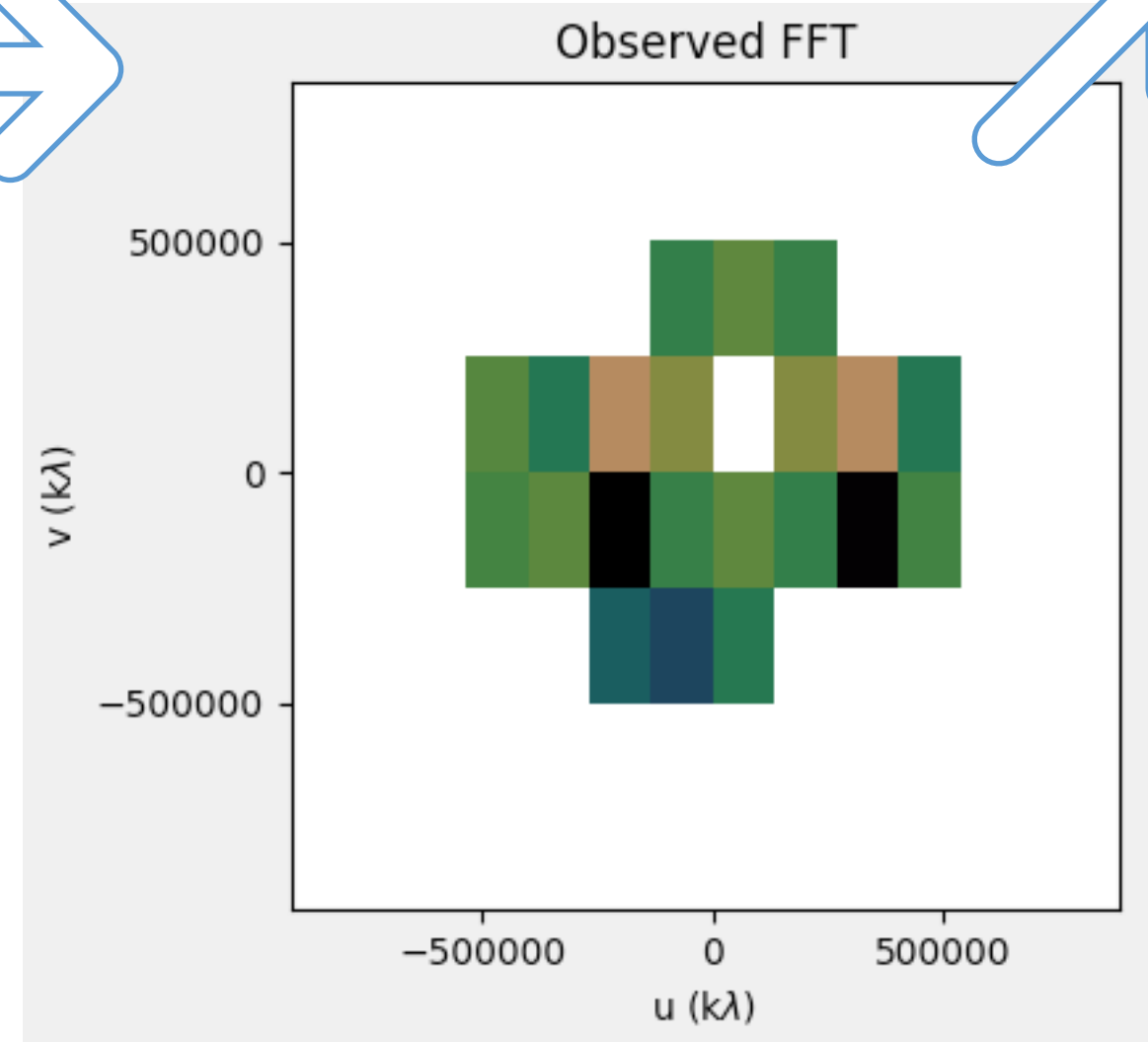
But, II measures the square of the visibility, so phase information lost.
However, there are ways to recover this.

- e.g. Cauchy-Riemann algorithm Nuñez et al. MNRAS (2012).
- e.g. three point intensity correlations Nuñez & Domiciano de Souza MNRAS (2015).

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The VERITAS spacing is okay for large structure, but not for fine details

8h observation with VERITAS for a <10mas giant "solar-like" star at 20° declination

$m_v < 6$

Model Image

Sol

NASA

3.5 mas

uv-Coverage

East-West (km)

Model FFT

Observed FFT

Observed Image

prelim.

prelim.
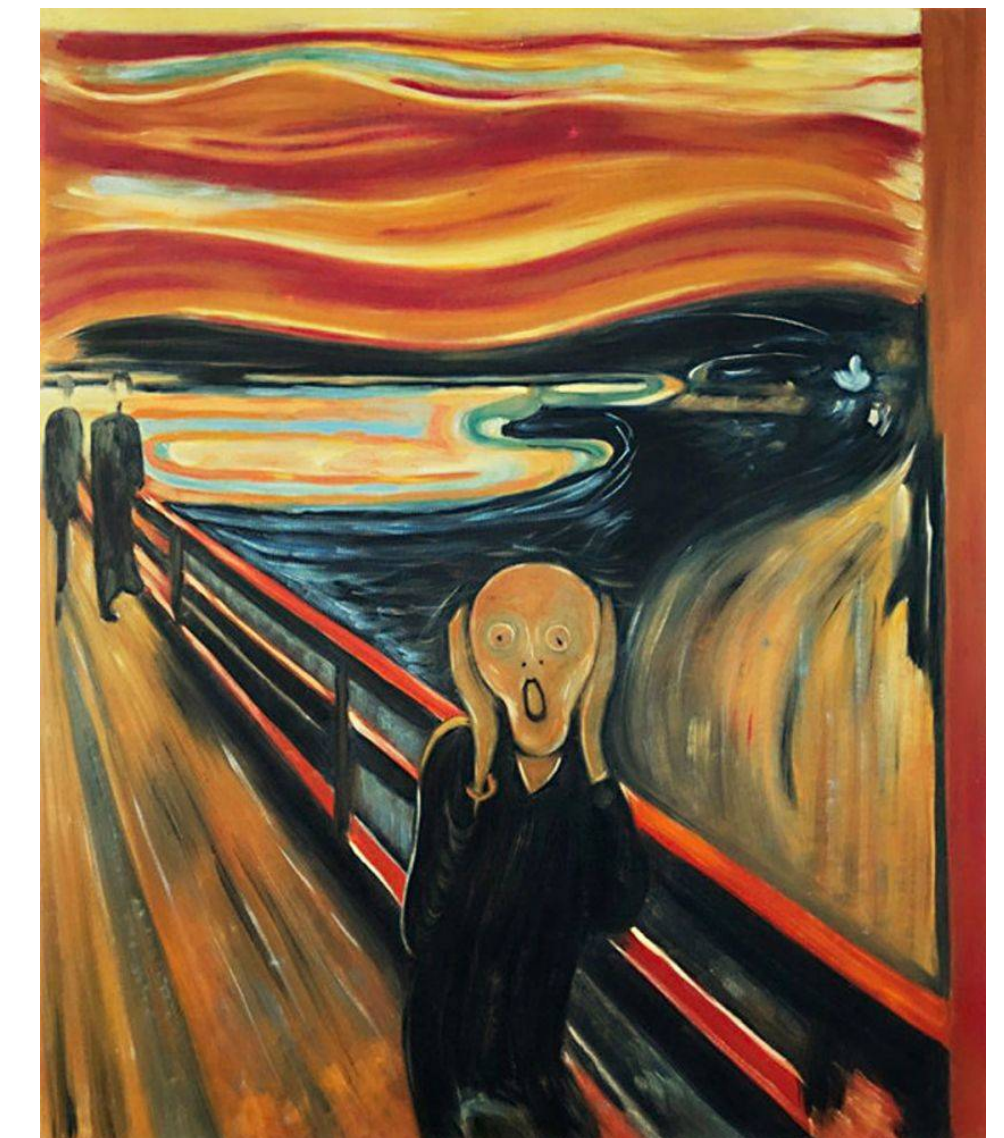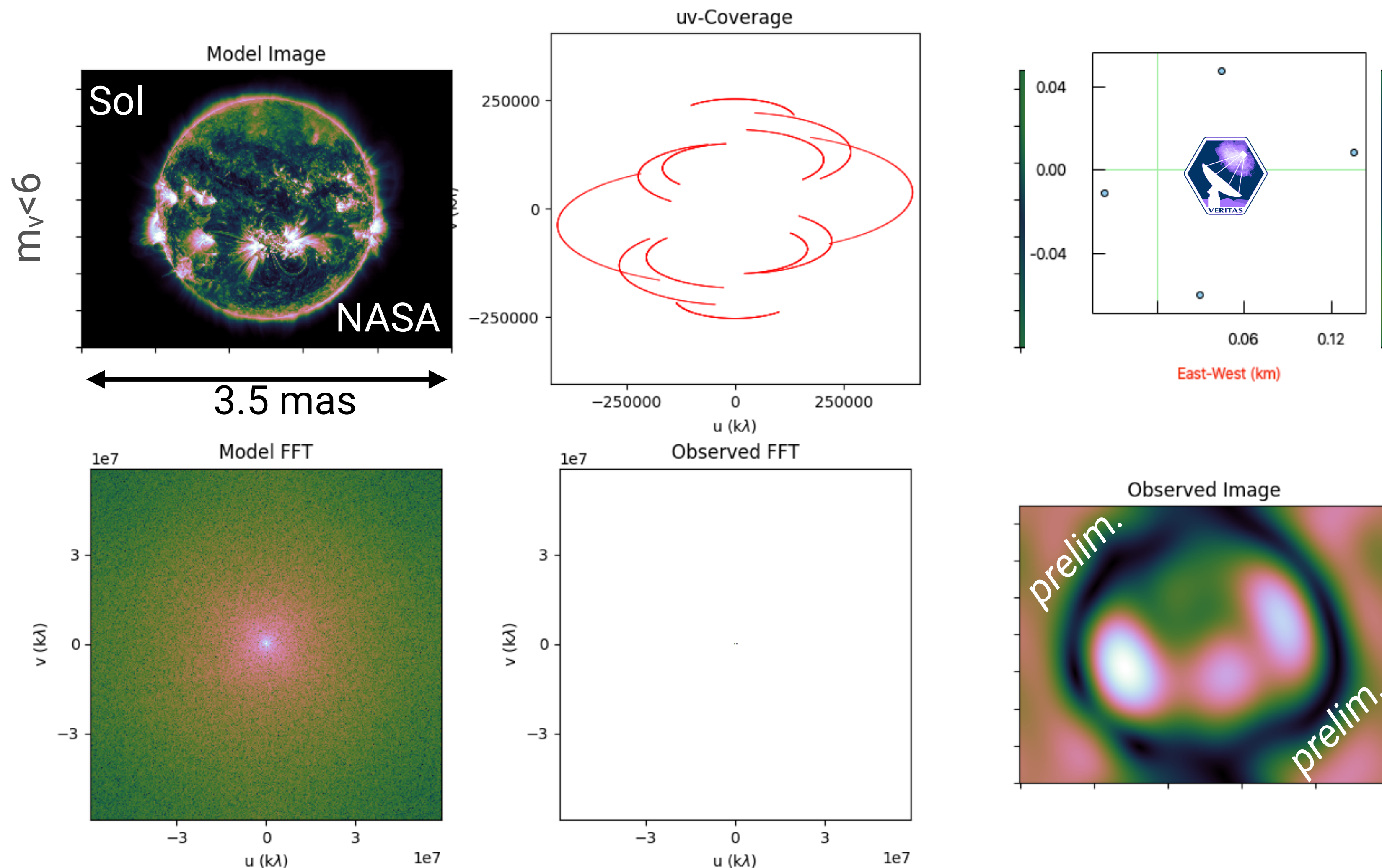
To do:
- *estimate noise*
- *phase recovery*
- **Get more telescopes**

Simulation adapted from the friendlyVRI
https://crpurcell.github.io/friendlyVRI/

** *FFT sampling effects only* **

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The VERITAS spacing is okay for large structure, but not for fine details

2h observation with CTA-S SSTs for a <10mas giant "solar-like" star at -20° declination

$m_V < 4$

Model Image

Sol

NASA

3.5 mas

uv-Coverage

Model FFT

Observed FFT

Observed Image

prelim.

prelim.

East-West (km)
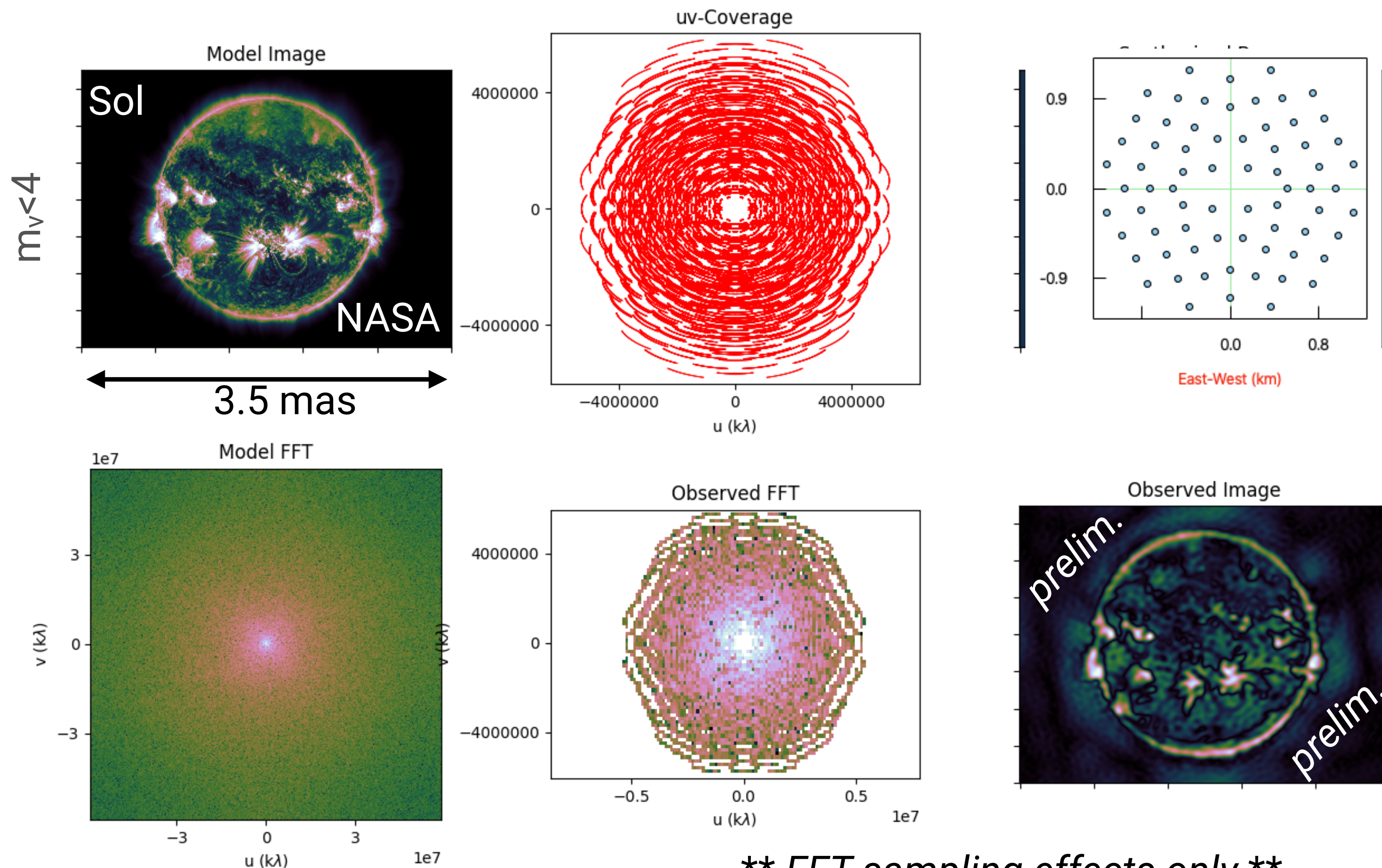
to do:
- estimate noise
- phase recovery methods
  - e.g. Cauchy-Riemann algorithm Nuñez et al. MNRAS (2012).
  - e.g. three point intensity correlations Nuñez & Domiciano de Souza MNRAS (2015).

*** FFT sampling effects only ***

Simulation adapted from the friendlyVRI
https://crpurcell.github.io/friendlyVRI/

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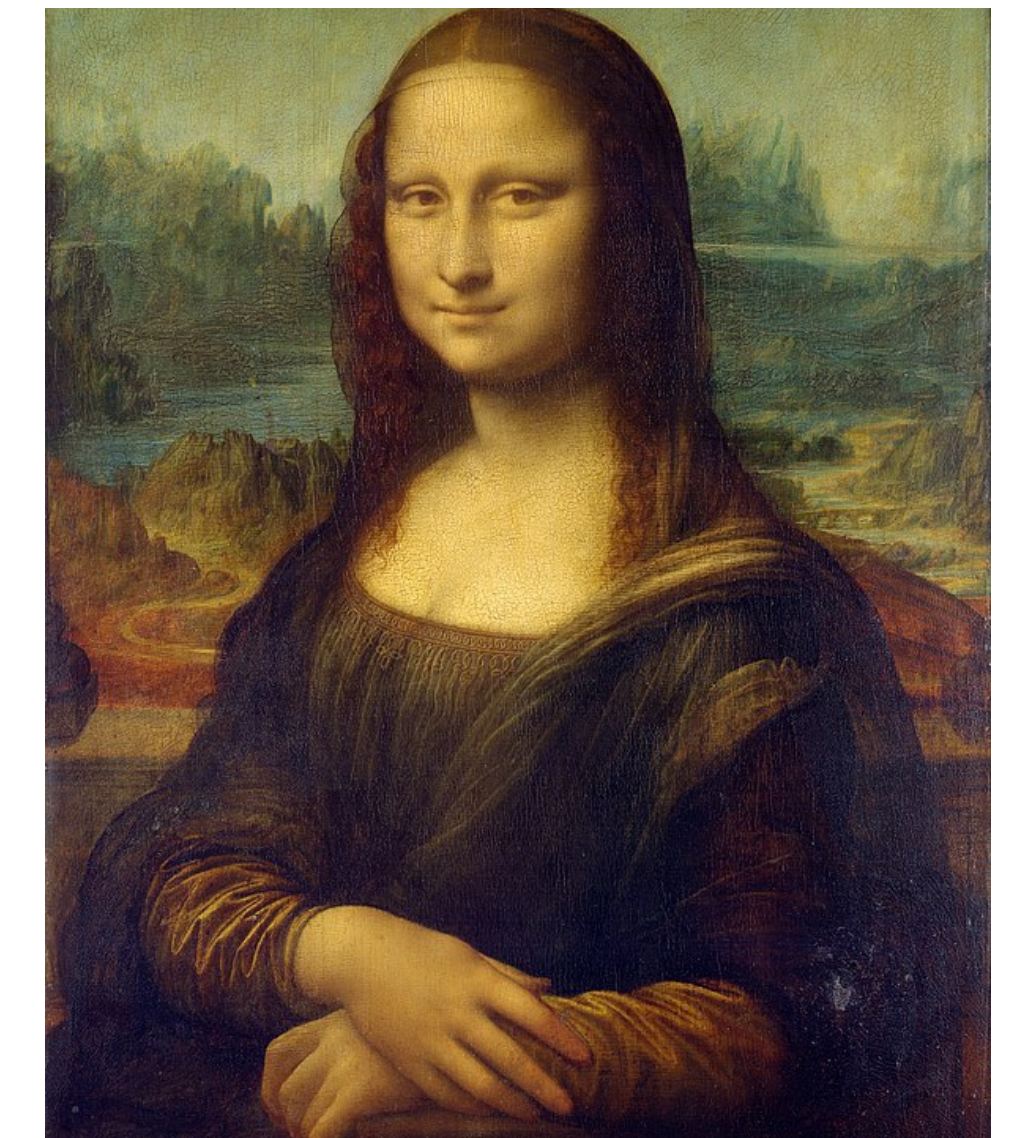
8h observation with VERITAS for a <1mas "solar-like" star at 20° declination

Model Image

Sol

NASA

$m_v < 6$

1mas

uv-Coverage

Model FFT

Observed FFT

East-West (km)

Observed Image

prelim.

prelim.
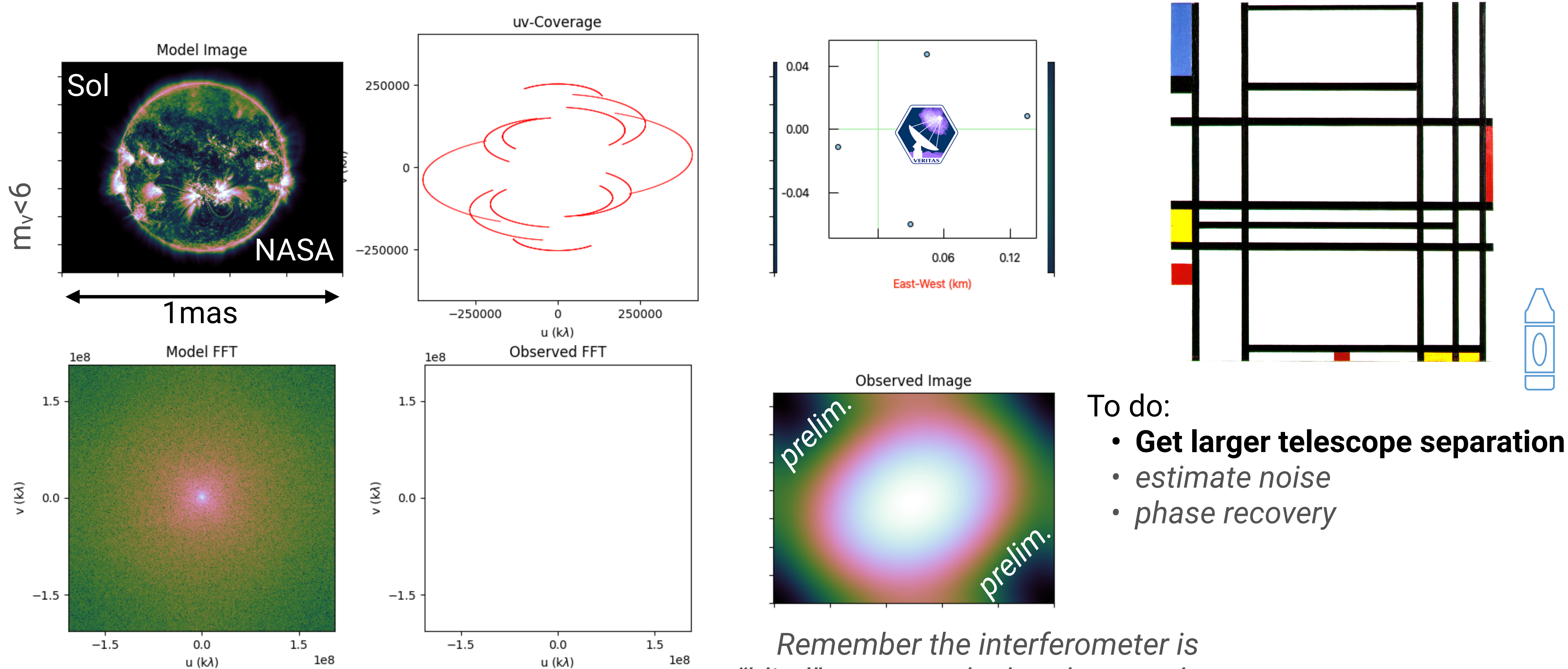
To do:
- **Get larger telescope separation**
- *estimate noise*
- *phase recovery*

Remember the interferometer is "blind" to any scale that does not have a baseline measurement

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8h observation with CTA-S MSTs for a <1mas "solar-like" star at -20° declination

Model Image

Sol

NASA

1mas

$m_V<6$

uv-Coverage

East-West (km)

Model FFT

Observed FFT

Observed Image

prelim.

CTA?

prelim.
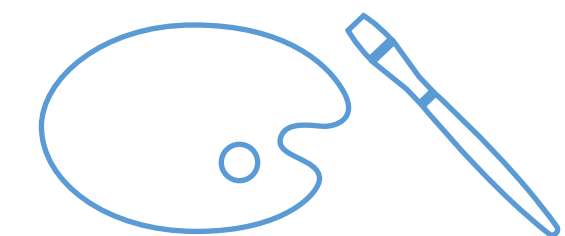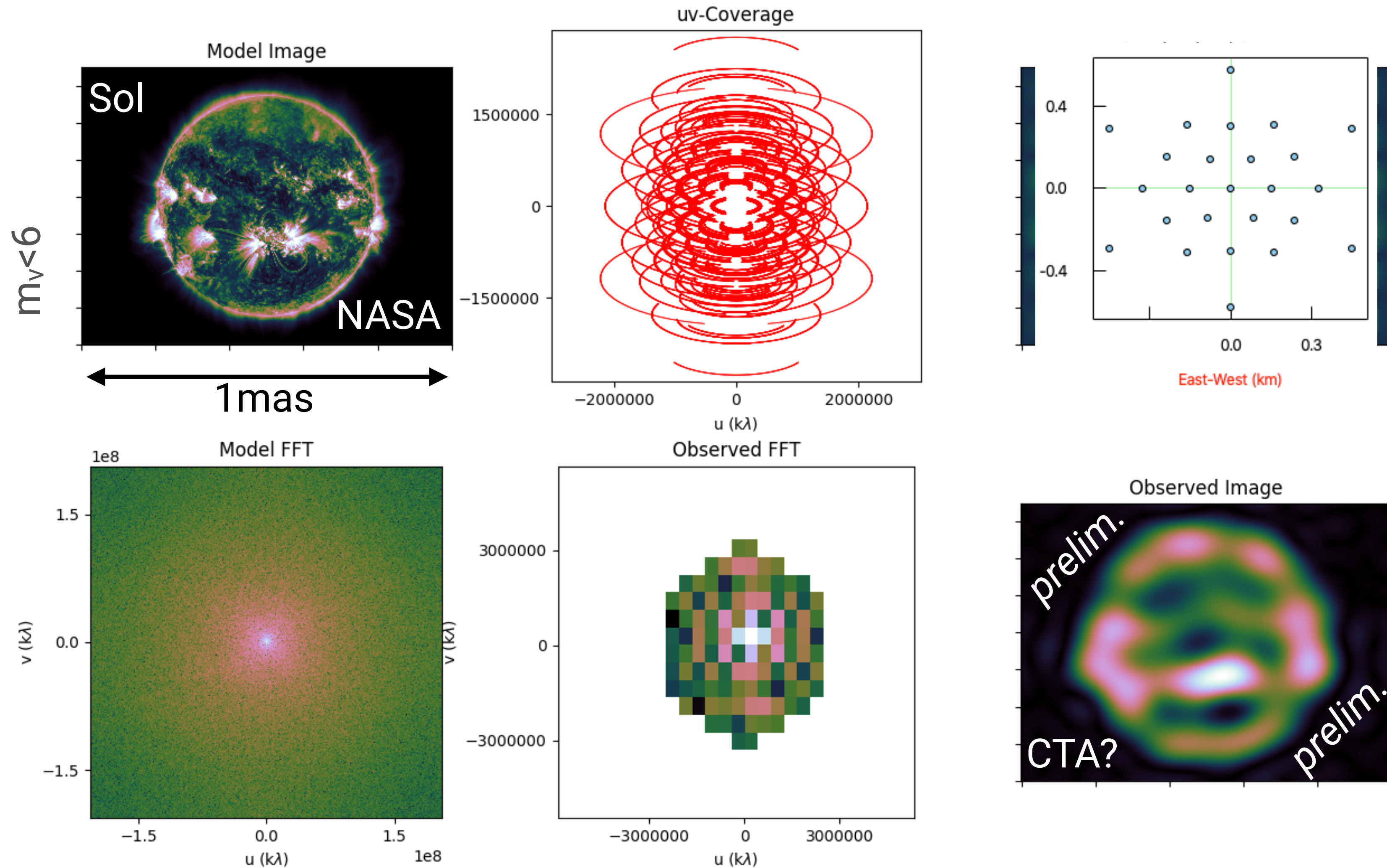
To do:
• estimate noise
• phase recovery methods

Simulation adapted from the friendlyVRI
https://crpurcell.github.io/friendlyVRI/

*** FFT sampling effects only ***

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2h observation with CTA-S SSTs for a <1mas "solar-like" star at -20° declination

Model Image

Sol

NASA

$m_v < 3.5$

1mas

uv-Coverage

East-West (km)

Model FFT

Observed FFT

Observed Image

prelim.

CTA?

prelim.
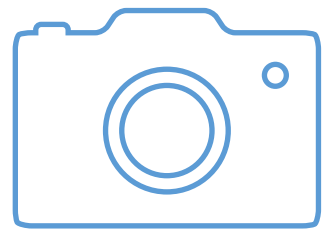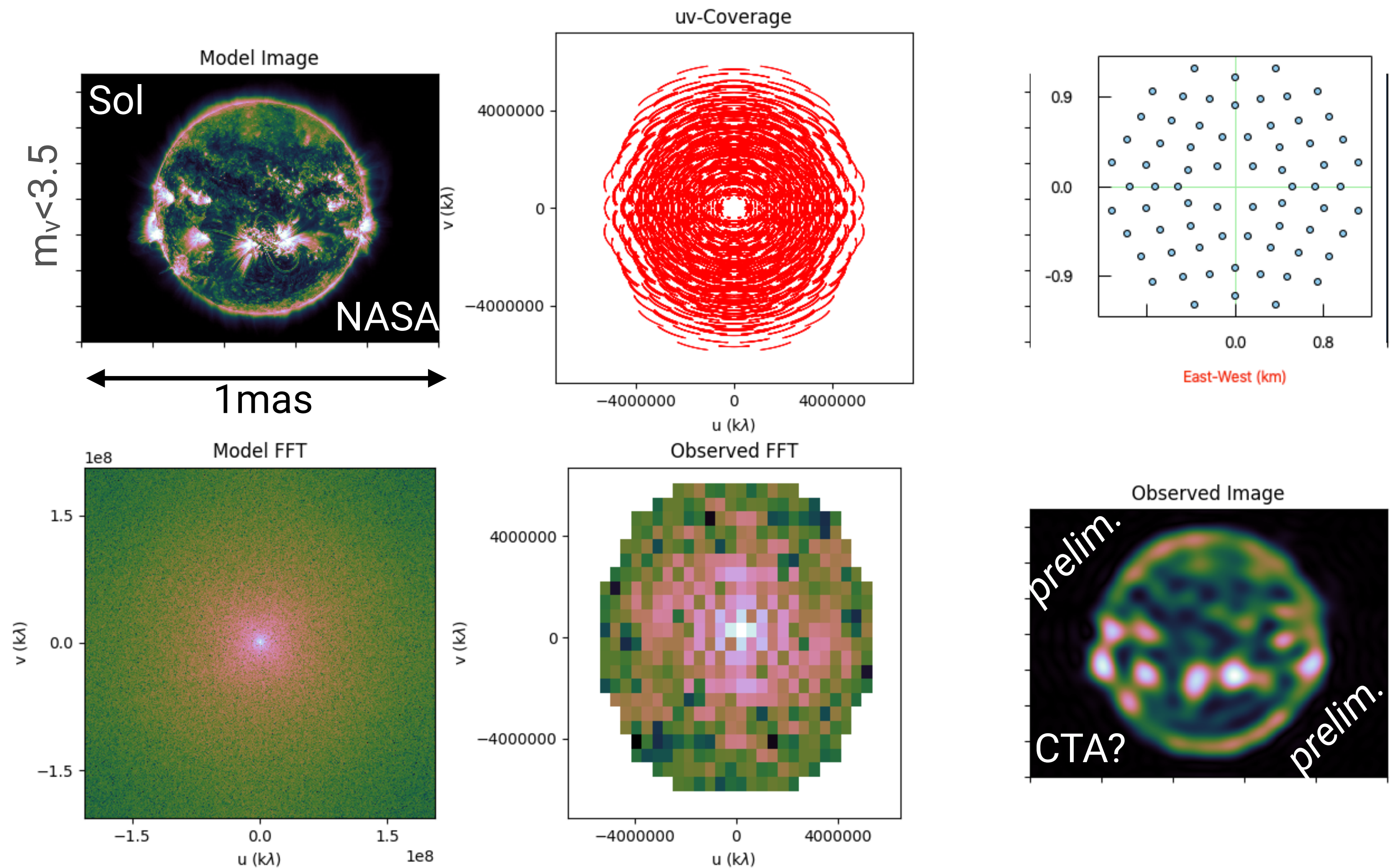
To do:
- estimate noise
- phase recovery methods
- **Count the star spots**

Simulation adapted from the friendlyVRI
https://crpurcell.github.io/friendlyVRI/

*** FFT sampling effects only ***

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Anything else?

See talk J. Holder
GAI11h We. 18:15

- Optical counterparts to FRBs?
- Fast transients?
- Free space optical communications?
- … ?

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Free Space Optical Communication

Deep-Space Optical
Communications
photonics.com

aka OSETI

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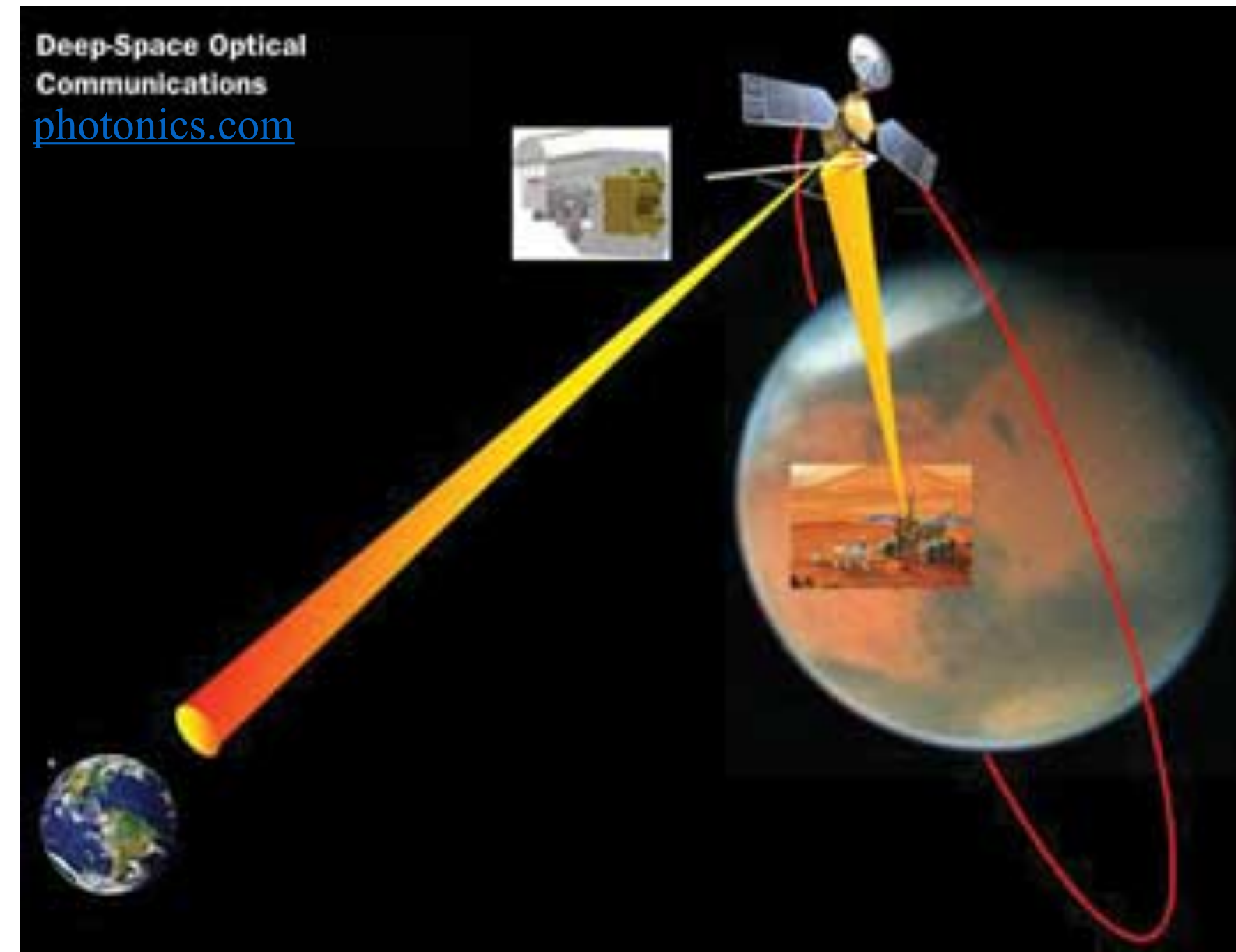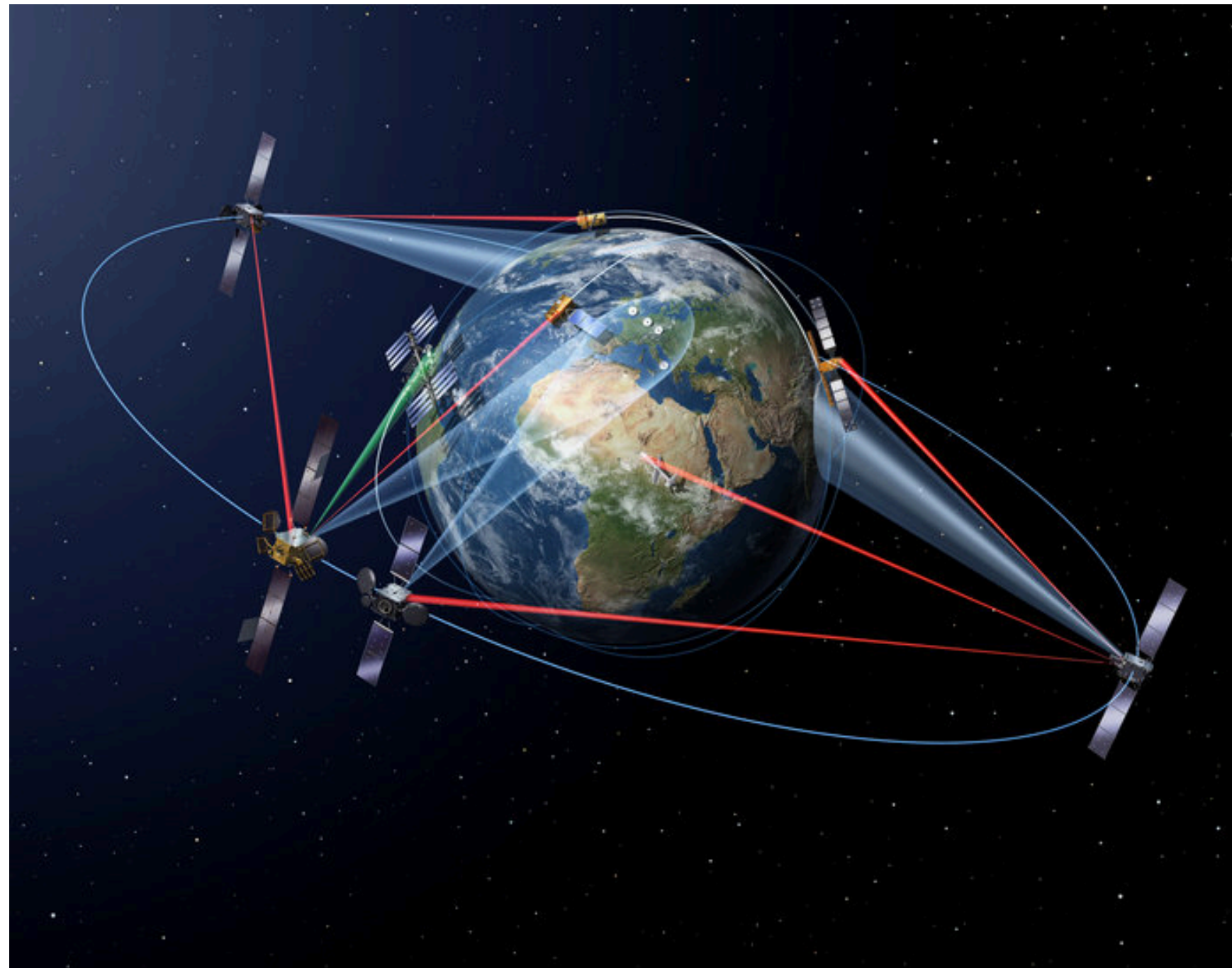
WHY OPTICAL RATHER THAN RADIO?

Idea first floated by R.N. Schwartz & C.H. Townes
'Interstellar and Interplanetary Communication by Optical Masers' *Nature* **190**, 205 (1961).

- **It is easier to deal with noise**
  - radio waves contend with interference from radio antennas, radio stations, the receiver itself adds noise (thus can require cooling), …
  - for optical the only significant source of terrestrial interference is lightning & Cherenkov radiation

- **Pulsed lasers can easily outshine the host star**
  - no known natural sources would have photons within a few ns of each other
    - ➡ could easily be 1000x brighter in the receiving telescope

- **Much easier to form a narrow beam of light**
  - a radio transmitter 100 ly distant & projecting omni-directionally would require 5800 trillion watts to be detectable ~ 7000x the electricity-generating capacity of the USA!
  - width of beam $\propto$ wavelength of beam / diameter of the antenna used
    - ➡ $\lambda_{optical} \ll \lambda_{radio}$

M. Ross *IEEE Spectrum* **7**, 32 (2006).

Just need a suitable optical light bucket as a receiver…

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How do Cherenkov telescopes compare?

The Additional IACT Advantages

The large field of view of the cameras helps to
- remove background signals
- monitor multiple stars simultaneously

3.5° camera can monitor ~45-150 stars (V<12) in a single pointing

	Detector	λ [nm]	Sensitivity [ph m^{-2}]
VERITAS[1], 12m	3pmt / <5ns	300-600	**1**
STACEE[2], heliostats	pmt ~12ns	300-600	10
Planetary Society[3], 1.8m	pmt / ~5ns	300-800	60
Harvard Oak Ridge[4], 1.5m	2 apd / 5ns	450-650	100
Lick Obs[5], 1m	2 apd / <1ns	950-1650	40
Princeton[6], 0.9m	2 apd / 5ns	450-650	80
Leuschner Obs[7], 0.8m	3 pmt / 5ns	300-700	41
METI / Boquete Obs[8], 0.5m	1pmt / 25ns	350-600	67

[1] Abeysekara et al. (2016)
[2] Hanna et al. (2009)
[3] Mead (2013)
[4] Howard et al. (2004)
[5] Maire et al. (2014)
[6] Howard et al. (2004)
[7] Korpela et al. (2011)
[8] Schuetz et al. (2016)

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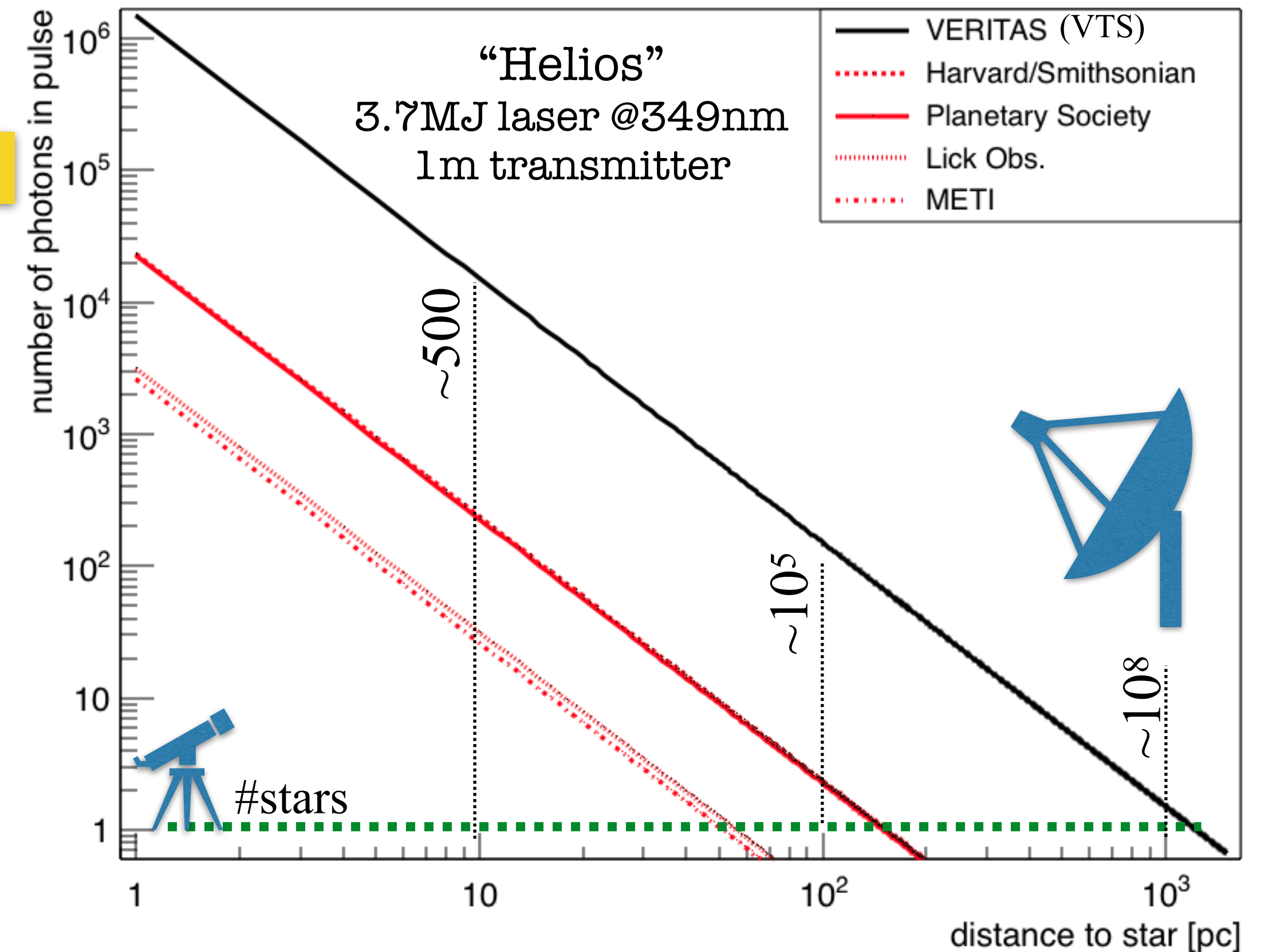
Summary

- IACTs are (not)surprisingly good optical telescopes when it comes to photometry

  - large mirror surface means low scintillation and shot noise
  - low noise makes for good high time resolution photometry
  - angular resolutions *equivalent to VLBI* are possible

- Sub-mas angular scale resolution with IACTs has been achieved

  - through measurement of diffraction pattern in asteroid occultations of stars
  - and as an offline optical intensity interferometer
    - can be scaled to arbitrary number of telescopes
      - simple to add new telescopes with commercial fibre optics

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Backup

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Enhanced Current Monitor (ECM)

DATAQ Instruments
DI-710-ELS

16 channel ethernet data logger and data acquisition system

- **DC powered** — using same camera supply as flashers
- **Ethernet readout** or SD card
- **16 single ended**, 8 differential analogue inputs
- 14-bit ADC
  - ±0.012% of full scale measurement range
- Measurement range of ±10mV to ±10V (in 4 gain stages)
- Record up to 4,800Hz when connected to PC
  - For asteroid/FRB sampling at 2,400 Hz
  - For transiting exoplanet measurements sampling at 10Hz

gain	range	resolution	limit
1	±10V	±1.22mV	~13th mag?
2	**±1V**	**±122μV**	~11th mag
3	±100mV	±12.2μV	
4	±10mV	±1.22μV	

16 channel obs = 4,800/16 = 300 Hz/channel

2 channel obs = 4,800/2 = 2,400 Hz/channel

The advantage is the VERITAS cabling scheme made this plug & play

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Signal/Noise
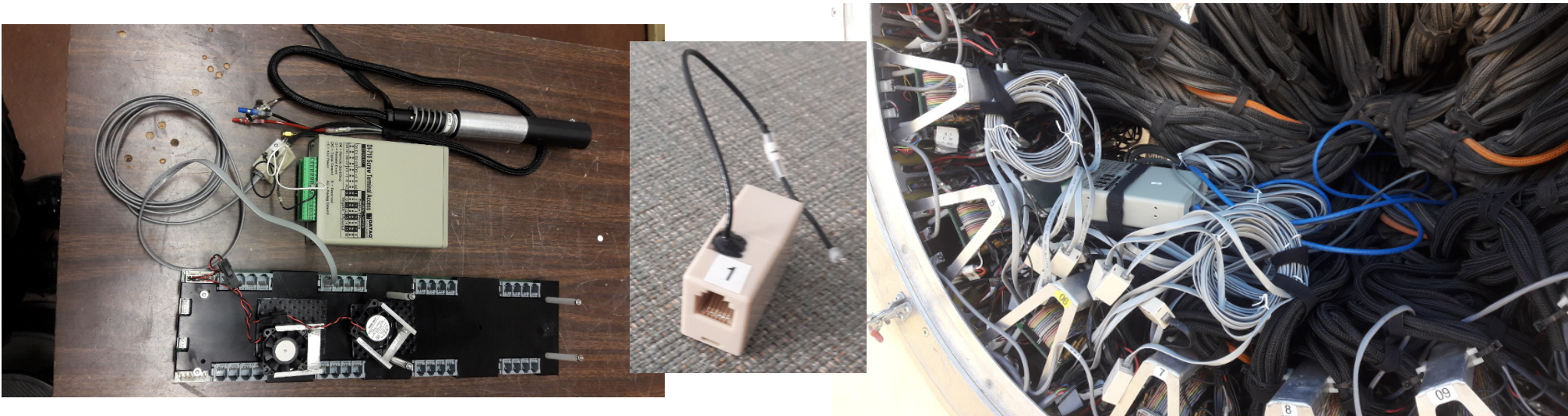
$$(S/N)_{\text{RMS}} = A \cdot \alpha \cdot n \cdot |\gamma_{12}(d)|^2 \cdot \sqrt{\Delta f \cdot T/2}$$

mirror
area   photon   correlation
       detection   electronics   observation
       efficiency   bandwidth   time

photons/m^2/s/Hz

$\alpha = 0.35$
cf NSII

Dish [m]	250 MHz	1 GHz
4	~0.5	~1
12	~5	~10
23	~20	~40

LeBohec & Holder *ApJ* **649**, 399 (2006)
$|\gamma_{12}|^2$=0.5 at 5σ to 14% accuracy in 5h for m_v=6.7
(3% for m_v=5)

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Sensitivity

magnitude

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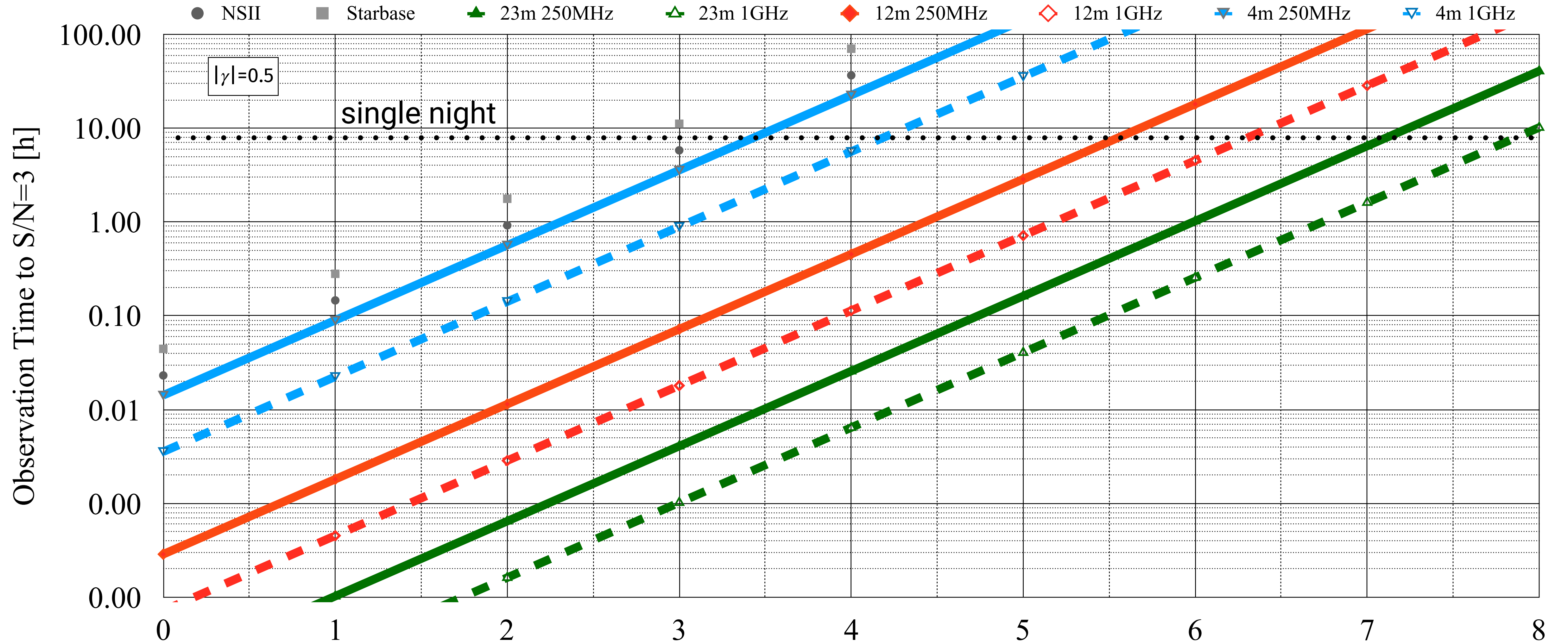
Table 2: Candidate sources from The Bright Star Catalogue: 35 stars brighter than $m_V = 2$ or hotter than $T_{eff} = 25{,}000$ K. Those whose angular diameters were measured already with the NSII [28] are marked with an asterisk (*).

Name	HR	θ [mas]	V_{rot} [km s^{-1}]	Spectral Type	T_{eff} [K]	m_V	Notes
Achernar, α Eri	472	1.9	250	B3 Ve	15 000	0.46	High V_{rot}, *
Rigel, β Ori	1713	2.4	30	B8 Iab	9 800	0.12	Emission-line star, *
λ Lep	1756		70	B0.5 IV	28 000	4.29	
Bellatrix, γ Ori	1790	0.7	60	B2 III	21 300	1.64	Variable, *
Elnath, β Tau = γ Aur [sic]	1791	1.5	70	B7 III	13 500	1.65	Binary system
υ Ori	1855		20	B0 V	28 000	4.62	Variable
HD 36960	1887		40	B0.5 V	26 000	4.78	Binary system
Alnilam, ϵ Ori	1903	0.7	90	B0 Iab	18 000	1.7	Emission-line star, *
μ Col	1996		150	O9.5 V	33 000	5.17	
β CMa	2294	0.5	35	B1 II-III	23 000	1.98	β Cep-type variable, *
Alhena, γ Gem	2421	1.4	30	A0 IV	9 100	1.93	*
S Mon	2456		60	O7 Ve	26 000	4.66	Pre-main-sequence
Sirius, α CMa	2491	5.9	10	A1 V	9 100	−1.46	*
EZ CMa	2583			WN4	33 000	6.91	Highly variable W-R star
Adara, ϵ CMa	2618	0.8	40	B2 Iab	20 000	1.5	Binary, *
Naos, ζ Pup	3165	0.4	210	O5 Ia	28 000	2.25	BY Dra variable, *
γ^2 Vel	3207	0.4		WC8	50 000	1.78	Wolf-Rayet binary, *
				O7.5	35 000		
β Car	3685	1.5	130	A2 IV	9 100	1.68	*
Regulus, α Leo	3982	1.4	330	B7 V	12 000	1.35	High V_{rot}, *
η Car	4210	5.0		peculiar	36 000	6.21	Extreme object, variable
Acrux, α^1 Cru	4730		120	B0.5 IV	24 000	1.33	Close binary to α^2 Cru
Acrux, α^2 Cru	4731		200	B1 V	28 000	1.73	Close binary to α^1 Cru
β Cru	4853	0.7	40	B0.5 IV	23 000	1.25	β Cep-type variable, *
ϵ UMa	4905		40	A0 p	9 500	1.77	α^2 CVn-type variable
Spica, α Vir	5056	0.9	160	B1 III-IV	23 000	0.98	β Cep-type variable
Alkaid, η UMa	5191	< 2	200	B3 V	18 000	1.86	Variable
β Cen	5267	0.9	140	B1 III	23 000	0.61	β Cep-type variable
τ Sco	6165		25	B0.2 V	26 000	2.82	
λ Sco	6527		160	B2 IV+	21 000	1.63	β Cep-type variable
Kaus Australis, ϵ Sgr	6879	1.4	140	B9.5 III	9 800	1.85	Binary, *
Vega, α Lyr	7001	3.2	15	A0 V	9 100	0.03	*
Peacock, α Pav	7790	0.8	40	B2 IV	19 000	1.94	Spectroscopic binary, *
Deneb, α Cyg	7924	2.2	20	A2 Iae	9 300	1.25	Variable
α Gru	8425	1.0	230	B6 V	13 000	1.74	*
Fomalhaut, α PsA	8728	2	100	A4 V	9 300	1.16	With imaged exoplanet, *

Table 5. Main-sequence stars, according to their spectral type (top) and apparent magnitude (bottom), observable from Kitt Peak.

Spectral type	Number of fully resolved stars	Overlap with CHARA	Number of partially resolved stars
M	230	230	0
K	729	726	0
G	424	282	0
F	431	118	52
A	364	77	348
B	205	44	328
O	4	0	6
Total	2387	1450	734

Apparent magnitude	Number of fully resolved stars	Number of partially resolved stars	Approximate integration time[a]
≤1	7	0	≪1h
1 to 2	18	0	≪1h
2 to 3	76	0	≪1h
3 to 4	199	5	0.2 h
4 to 5	667	52	1.24 h
5 to 6	1420	677	8 h
Total	2387	734	

Note. [a]In order to obtain angular size measurement with a precision of ~10 per cent.

SPIIFy
Pilyavsky et al. *MNRAS* **467**, 3048 (2017)

Dravins et al *NewAR* **56**, 143 (2012).
Dravins et al *APh* **43**, 331 (2013).

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Remember these are never before achieved angular resolutions in the optical — we know that there are interesting things happening at these angular scales, but we can only predict some of what that might be...

η Carinae:
massive star, colliding wind binary, core collapse supernova / GRB progenitor

CTA resolution would be at scale of component stars

30.9 au

NB, II signal/noise is independent of spectral bandpass. Same resolution can be achieved in spectral lines not just continuum. Different wavelengths probe different optical depths
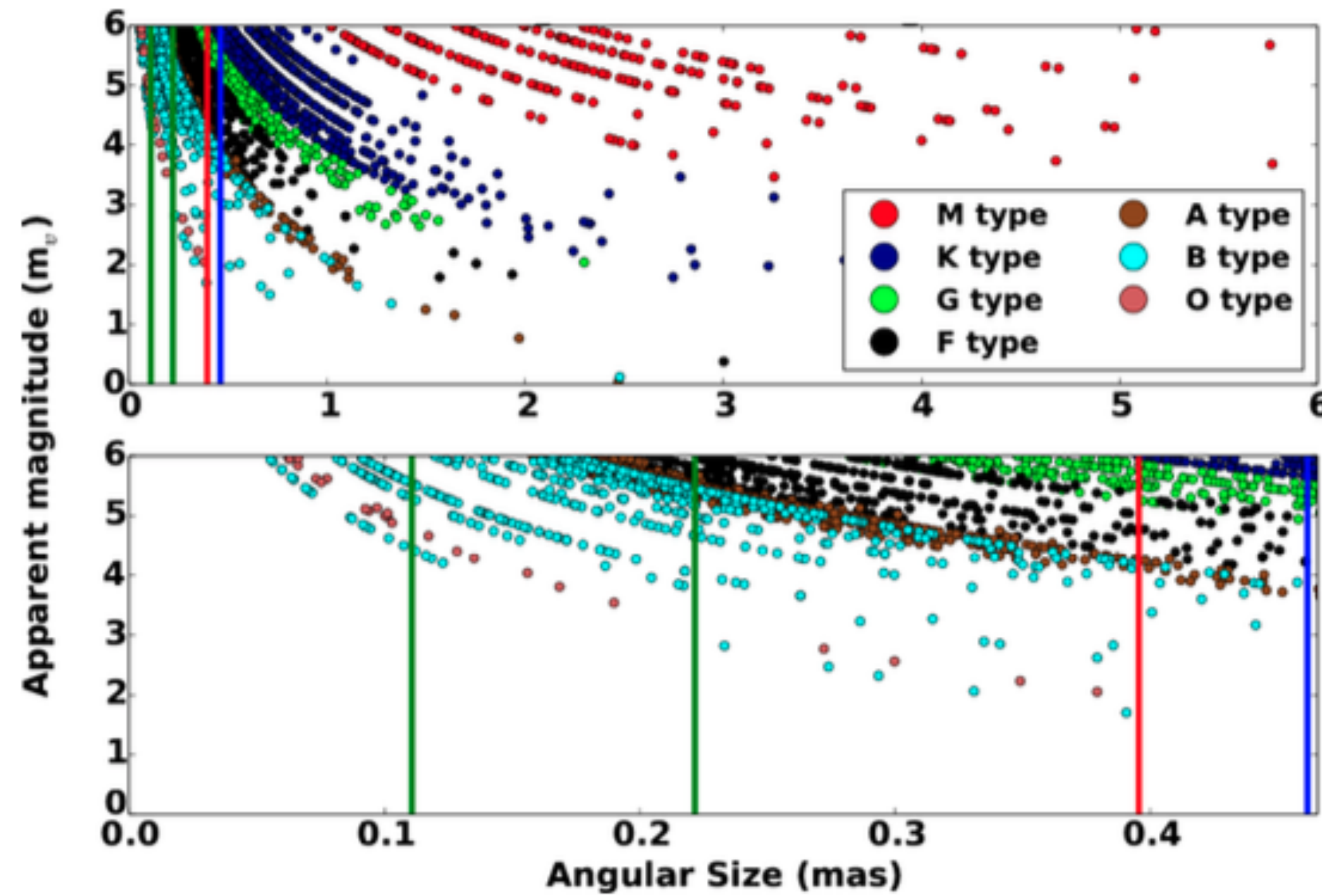
-> 3D imaging?
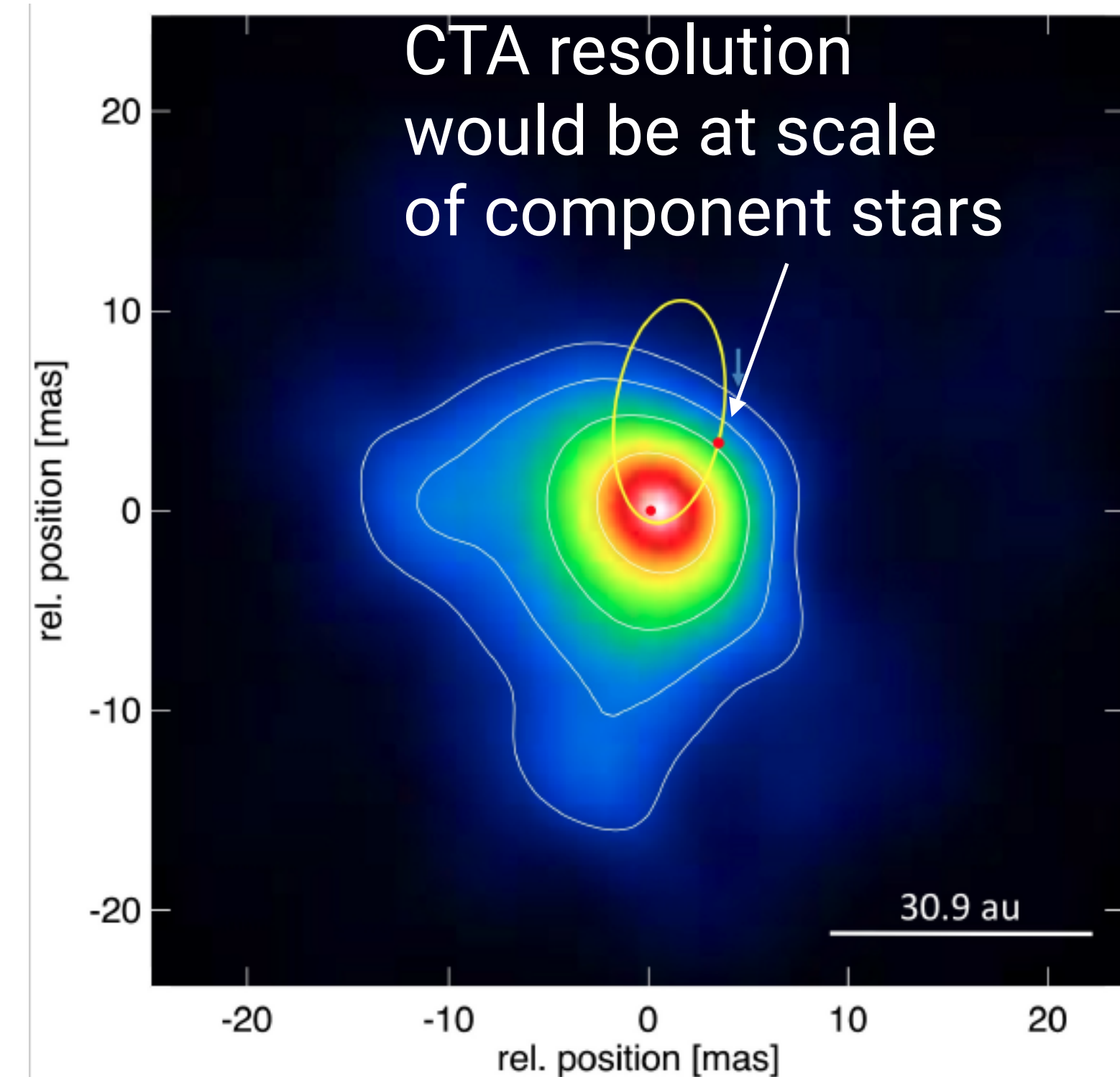
Weigelt et al. 'VLTI-AMBER velocity-resolved aperture synthesis imaging of η Carinae... Studies of the primary star wind and inner most wind-wind collision zone.'

A&A **594**, 106 (2016).

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Figure 6. Top: stellar magnitudes from the Bright Star Catalogue plotted as a function of their approximate angular size. The colours correspond to the spectral type, given in the legend. Bottom: identical plot, with a narrower range in angular size, showing the bounds where observations from Kitt Peak can fully resolve the star (~0.21 milliarcsec) and bounds where stars will be partially resolved (~0.11 milliarcsec).

SPIIFy
Pilyavsky et al. *MNRAS* **467**, 3048 (2017)
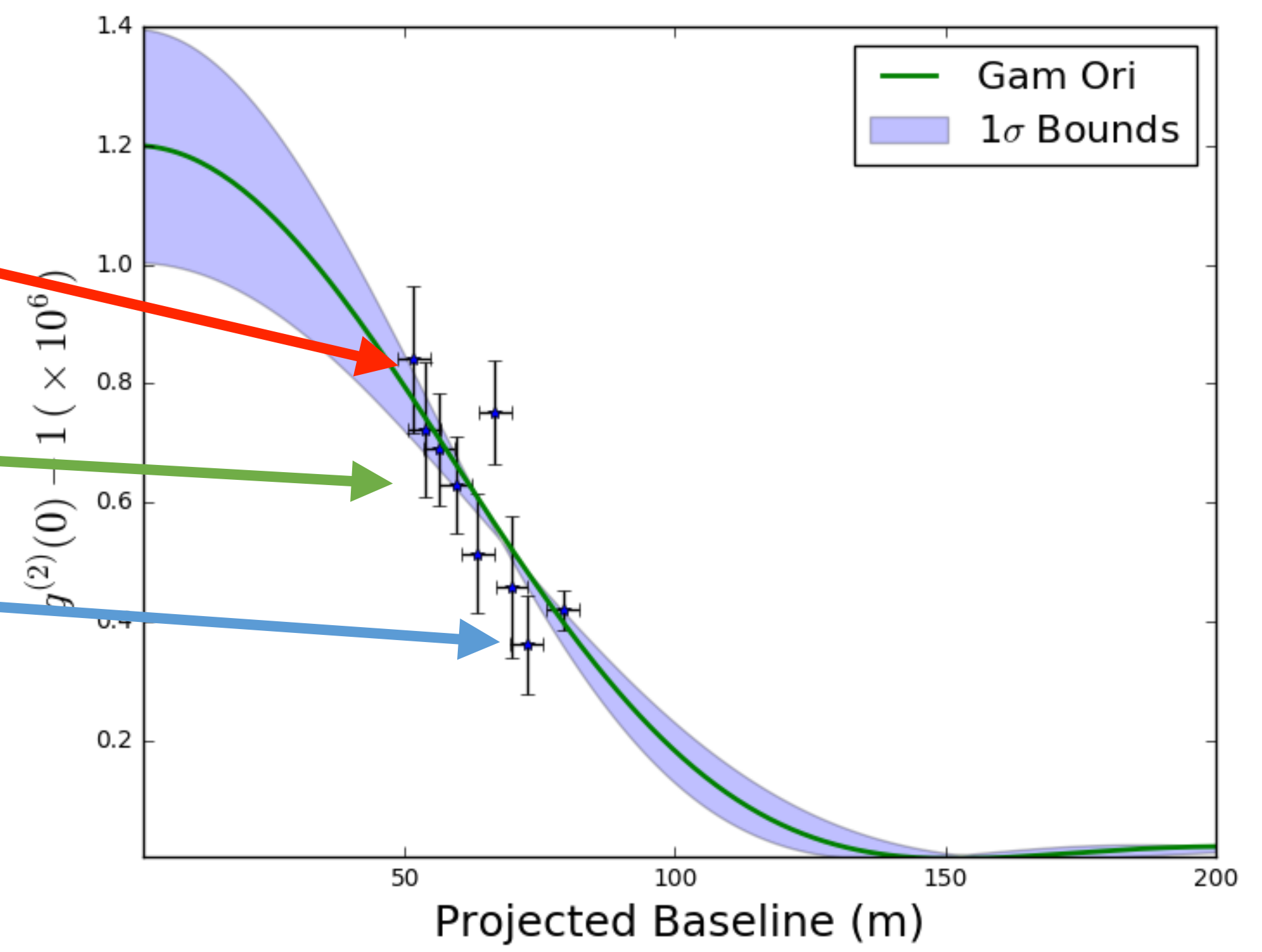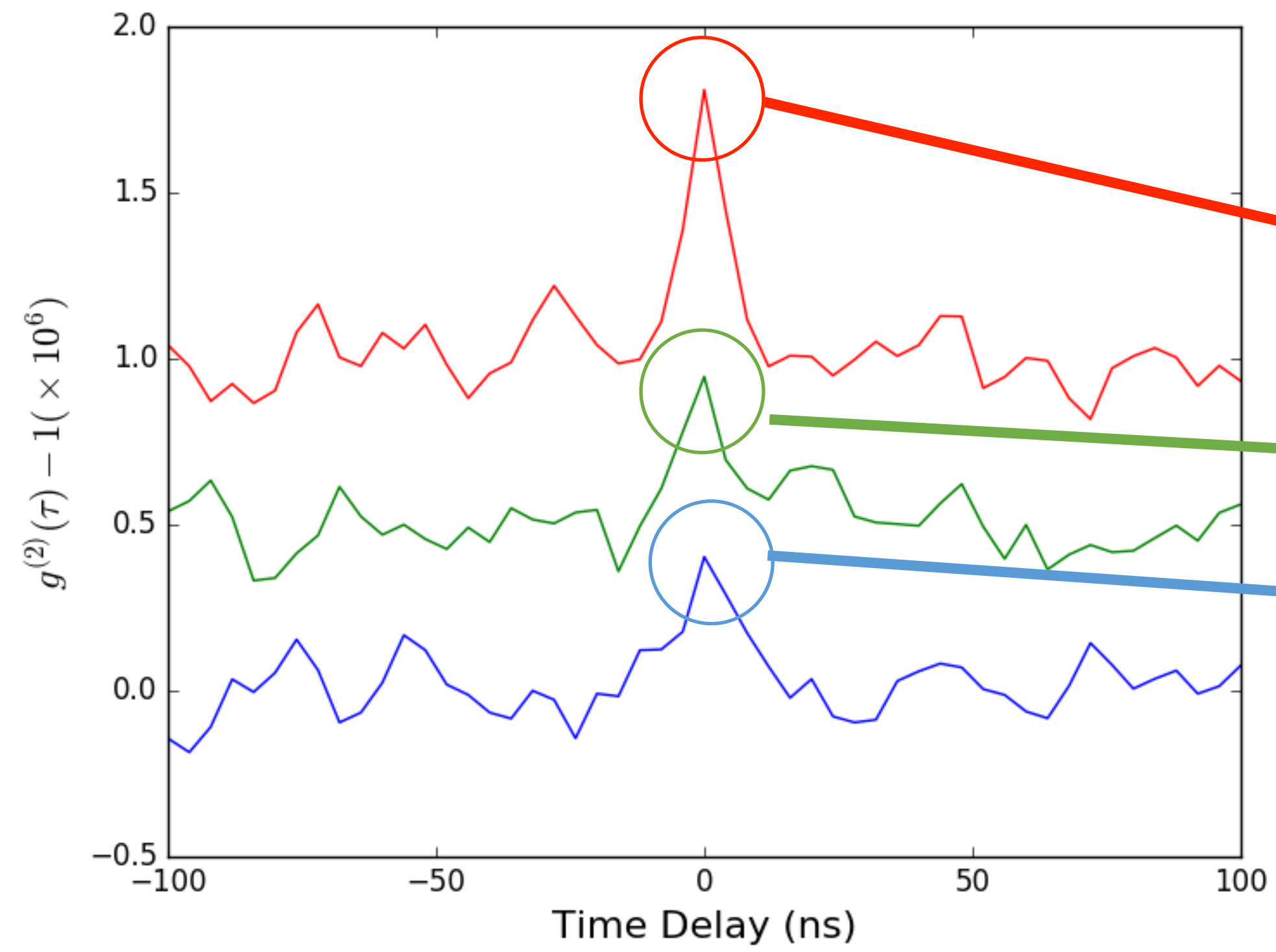
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son 2019

The Additional IACT Advantages

The large field of view of the cameras helps to
 • remove background signals
  • monitor multiple stars simultaneously

VERITAS can monitor ~45-150 stars (V>12) in a single pointing

OSETI event selection criteria

• They appear in the same place in all four telescope cameras

• They have the same intensity in each telescope

• They are point-like (c.f. optical point-spread function)
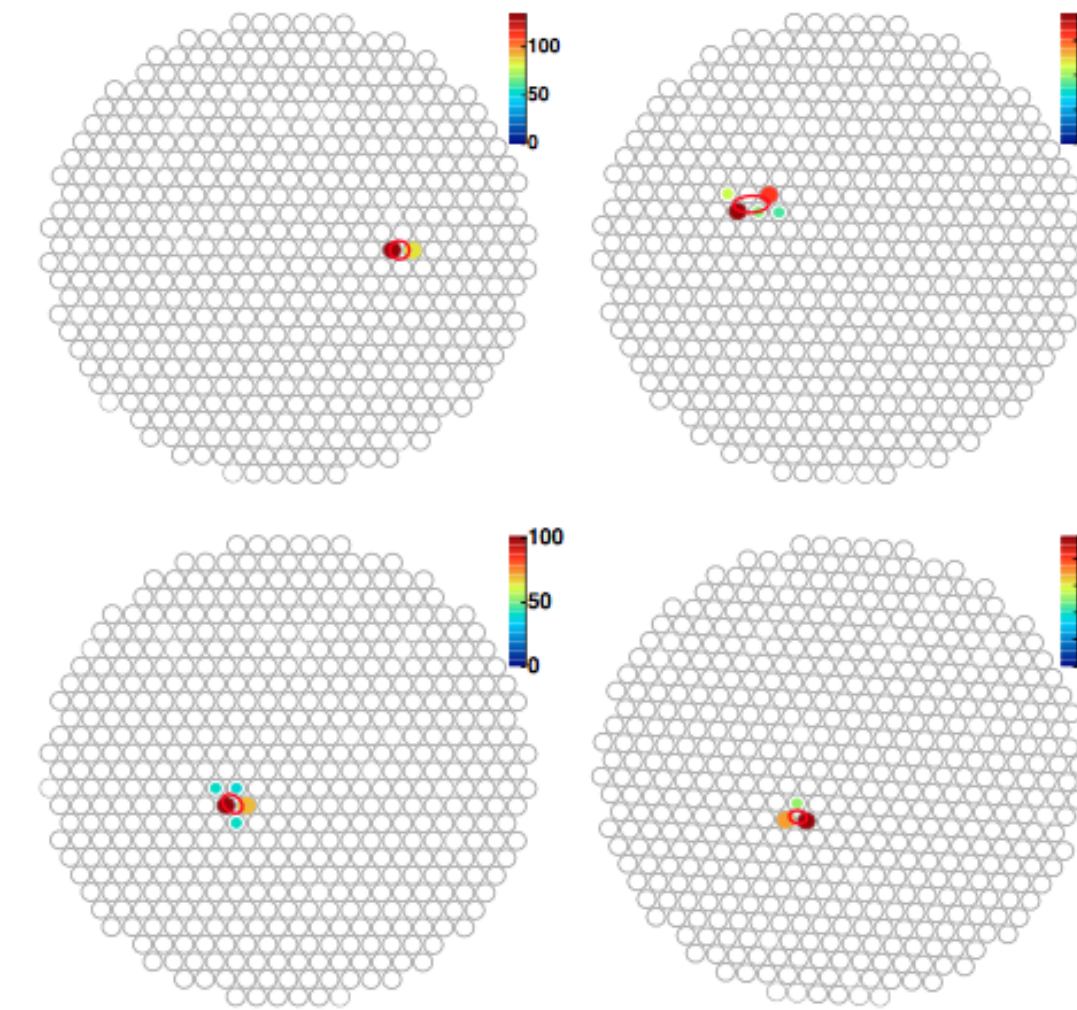
Cosmic rays show parallax due to shower max. only being a few km in altitude
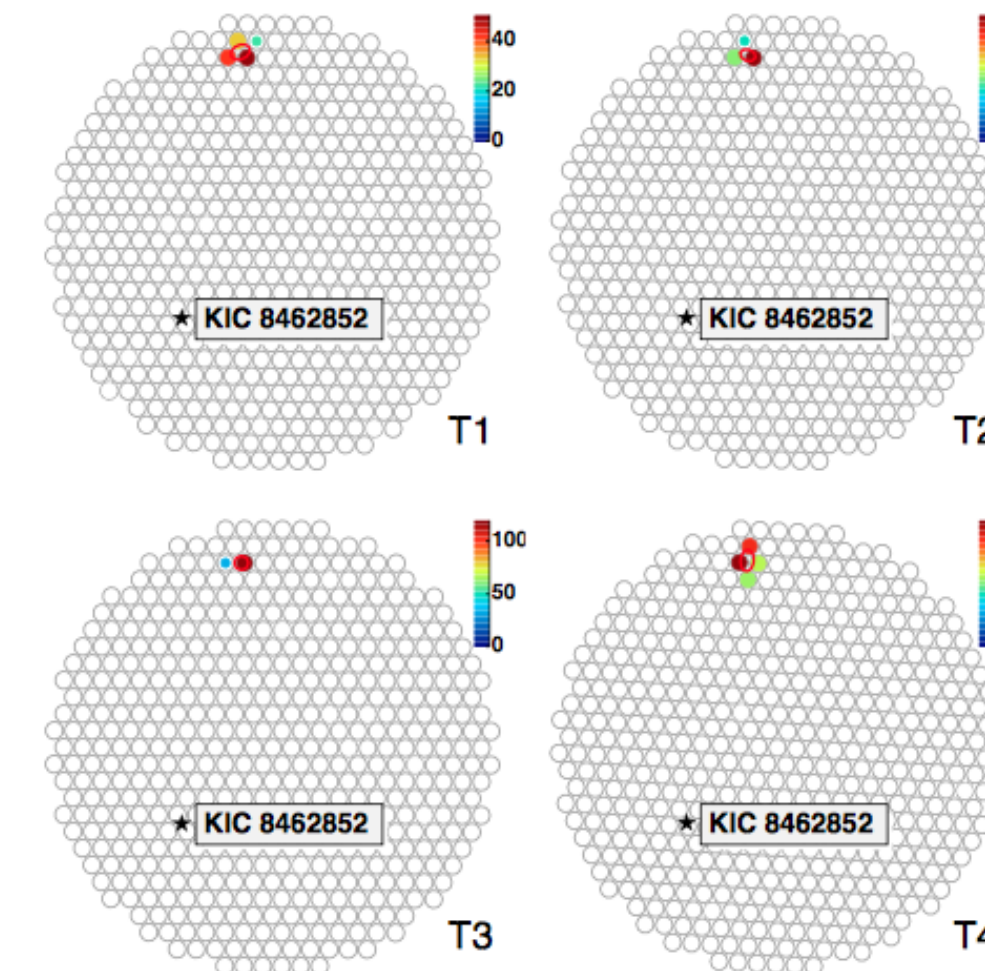
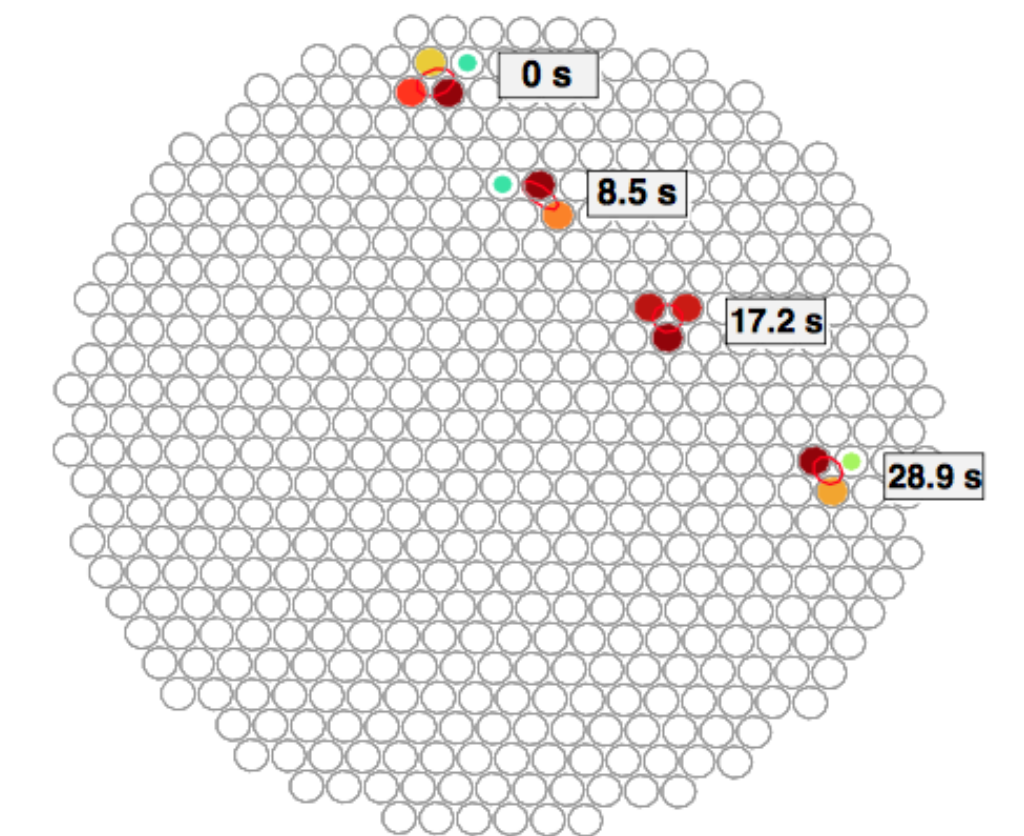Shooting stars/satellites will move through the camera

Fig. 3.— Point-like events generated by an object moving across the field-of-view of VERITAS over the course of 28.9 seconds on MJD 57283. **Left:** A single event viewed by all four telescopes. **Right:** A subset of the eight recorded events illustrating the motion of the image across the camera of a single telescope.

Abeysekara et al. *Ap.J* **818**, 33 (2016)

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